Technoeconomic assessment of a PVT-based solar combined cooling heating and power (S-CCHP) system for the University Campus of Bari

María Herrando[1,2], Antonio M. Pantaleo[2,3], Kai Wang[2], Christos N. Markides[2,*]
[1] Fluid Mechanics Group, University of Zaragoza, Zaragoza, Spain
[2] Clean Energy Processes (CEP) Laboratory, Department of Chemical Engineering, Imperial College London, London, UK
[3] Department of Agro-Environmental Sciences, University of Bari, Italy
e–mail: maria.herrando11@imperial.ac.uk, a.pantaleo@imperial.ac.uk, kai.wang@imperial.ac.uk, c.markides@imperial.ac.uk

ABSTRACT

In this work we analyse the year-round technoeconomic performance of a solar combined cooling, heating and power (S-CCHP) system that features polymeric flat-box PVT collectors coupled via a thermal store to an absorption chiller. The hourly space heating (SH), cooling and electricity demands of the University Campus of Bari are used as inputs to a model developed in TRNSYS. Current electricity and gas prices are considered in order to estimate the annual cost savings which, together with the system's investment cost, allow an estimation of its payback time (*PBT*). The results are then compared to a PV system that matches the electricity demand of the Campus (including the electricity required to run the current HVAC system for air-conditioning). The results show that the main limiting factor for the implementation of the S-CCHP system is the roof-space availability in this application. A system with an installed power of 1.68 MW_p can cover 14% of the SH, 66% of the cooling and 17% of the electrical demands of the Campus. The system's *PBT* is estimated at 19.3 years, which is 3 times higher than the *PBT* of a PV system of the same installed power, nevertheless, the proposed S-CCHP system has the potential to displace 1,170 tons CO_2/year, or 50% more than the equivalent PV solution.

KEYWORDS

solar energy, hybrid PVT, absorption chiller, energy modelling, payback time, energy demand.

INTRODUCTION

Fossil fuels are considered as primary energy sources to satisfy the growing energy demand worldwide, which is attributed to population growth and industrialization [1]. It is estimated that in 2035 more than 80% of the energy consumption in developed countries will be satisfied by fossil fuels [2]. Solar energy can play a central role in reducing these trends and increasing the penetration of renewable energy systems, particularly in buildings, which account for 40% of the total energy consumption and 36% of the greenhouse gases in Europe [3].

In particular, solar heating and cooling (SHC) technologies have been gaining increasing attention recently, as part of wider efforts to decarbonise the overall energy system and in particular the building sector [4]. SHC technologies 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.

* Corresponding author

Different types of solar thermal (ST) collectors, namely flat plate (FPC), evacuated tube (ETC), parabolic through (PTC), etc., can be used to harvest solar energy in SHC and/or solar power systems [1,5–9]. An alternative to systems based on ST collectors relies on PV systems coupled to electrically-driven reversible heat-pump/chiller (HP/CH) units [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, generate both electricity and a useful thermal output simultaneously from the same aperture area, and achieve a higher overall efficiency than separate stand-alone systems [11–14]. Therefore, the integration of PVT systems as the solar source of SHC technologies allows the simultaneous generation of DHW, SH, cooling and excess electricity, and thus has the potential to cover the heating, cooling and power demands of buildings.

Most of the research in literature have focused on integrating ETC [15], FPC [10] or PTC [16] with absorption (AbCH) or adsorption chillers (AdCH). There are also some studies that have considered CPCs coupled with single or double effect LiBr-H_2O AbCH [17], solar desiccant and evaporative cooling (DEC) systems [18]. Most of the studies concerned with PVT systems have focused on combining concentrated PVT (CPVT) collectors with LiBr-H_2O AbCH [19], while studies on flat-plate PVT collectors are more scarce [20]. However, a previous research concluded that the integration of PVT-water collectors with AbCH or AdCH is very promising [4]. Despite its potential, there are still very few companies worldwide commercialising PVT collectors [12], which in most cases do not have optimised designs. In an attempt to overcome this, previous work by the authors [21] 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.

Therefore, this research aims to investigate the technoeconomic potential of a solar combined cooling heating and power (S-CCHP) system based on this novel flat-box PVT collector coupled with an AbCH unit (single-effect LiBr-H_2O) via a thermal store, for the combined provision of SH, cooling and electricity in the University Campus of Bari, Italy.

METHODOLOGY

The S-CCHP system has been modelled in TRNSYS [22], where hourly transient simulations considering real weather data [23] are conducted over a year. The main outputs are the electricity and thermal energy generated by the PVT collectors, the amount of SH and cooling that can be covered by the proposed system and the auxiliary heating (natural gas) needs. Current electricity and natural gas prices are considered 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 proposed S-CCHP system. The electricity generation surplus at any time step is fed to the grid at a feed-in tariff (FIT) which corresponds to the electricity generation cost. The annual CO_2 emission reduction by the proposed system is also estimated based on the current CO_2 emission factors in Italy. The results are then compared to a PV system that matches the electricity demand of the Campus (including the electricity required to run the current HVAC system for air-conditioning). To size the systems, the limiting factor is the available roof-space in the Campus' buildings (23,600 m^2).

S-CCHP system

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 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 Figure 1). The electrical output of the PVT collectors is used to match the Campus's annual electricity demand.

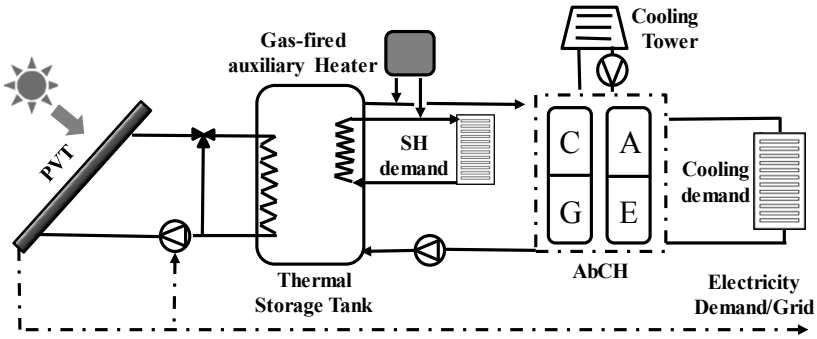

Figure 1. Schematic diagram of an S-CCHP system based on PVT collectors integrated with a single-effect LiBr-H_2O AbCH through a thermal store

PVT collector. Polycarbonate flat-box PVT collectors are proposed and investigated in this work, which improves the heat transfer from the absorber to the fluid by means of 2×3 mm channels [21]. The proposed PVT collectors are implemented in TRNSYS with Type 560 which was modified and adjusted in previous research [24] to match the thermal performance (η_{th}) curve shown in Eqs. (1-2). The PVT collector has a nominal electrical power of 240 W_p and an aperture area of 1.55 m^2. The nominal electrical efficiency (η_{el}) of the PVT collector is 14.7%, and the temperature coefficient of the PV cells is 0.45 %/K.

$$\eta_{th} = 0.726 - 3.325 \cdot T_r - 0.0176 \cdot G \cdot T_r^2 \quad (1)$$

$$T_r = \frac{\left(T_{fm} - T_a\right)}{G} \quad (2)$$

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

Stratified water storage tank. The tank is assumed to consist of 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 Figure 1). 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 through the variation of the V_t/A_{cT} ratio, where V_t is the tank volume in litres and A_{cT} is the total PVT collector area in square meters. 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 [25] to ensure adequate heat transfer.

Absorption chiller. Type 107 is used to model the AbCH. 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 65 ºC at least (60 ºC is the minimum temperature to start the cycle). Performance data of a commercial AbCH is considered for the modelling of this unit and the data files are normalised so different AbCH unit sizes can be modelled [26].

PV system

The PV system consists of a set of modules tilted at 30°, with a nominal power of 275 W_p and an aperture area of 1.44 m^2. The nominal electrical efficiency (η_{el}) of the PV modules is 16.9%, and the temperature coefficient of the PV cells is 0.40 %/°C. Assuming adequate distances between PV modules to maximise yield, it is estimated that 14 m^2/kW can be installed, thus the maximum installed power of the PV system is 1.68 MW_p (total available roof-space of 23,600 m^2).

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. The SH demand is 49.1 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 390,000 Nm^3 of natural gas. The DHW demand is negligible. The cooling demand is estimated to be 30.3 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 78.9 kWh/m^2-year. Figure 2 shows the monthly energy demand breakdown of the Campus.

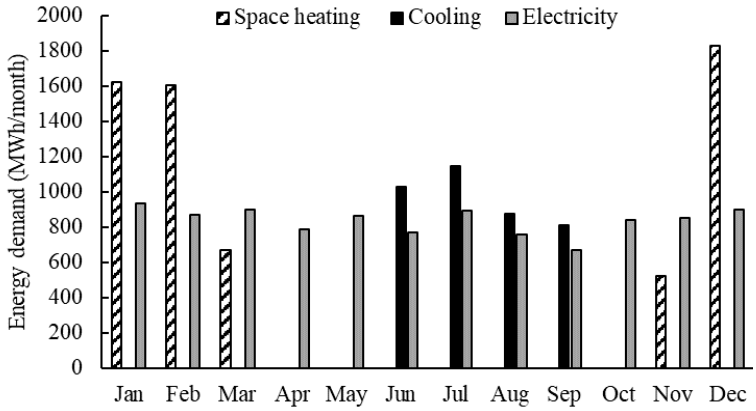

Figure 2. Monthly SH, cooling and electricity demand of the University Campus of Bari

Only monthly natural gas bills are available, so based on the information provided by the Campus heating system operator (Engie Servizi SpA), a flat profile from 8 am to 6 pm (10 hours/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 (Enel Energia), which is aggregated to estimate the hourly electricity consumption. To estimate the cooling demand, based on previous studies [27,28], it is assumed that during summer months (June to September), 60% of the total electricity consumption is consumed by the HVAC systems (with a COP of 3) to provide air-conditioning from 8 am to 6 pm (10 hours/day). These hourly SH, cooling and electricity demands are inputs to the TRNSYS model.

Economic analysis

The S-CCHP system's investment cost (C_0) is estimated from price lists available from solar retailers in the EU [29–31]. The main costs of the system are associated with the PVT collectors [21], storage tank [32], absorption chiller and cooling tower [4]. 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 [12]. The auxiliary heater price is not considered as the University Campus already has installed gas-fired boilers.

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 [33],

$$PBT = \frac{\ln\left[\frac{C_0 \cdot (i_F - d)}{FS_{S-CCHP}} + 1\right]}{\ln\left(\frac{1+i_F}{1+d}\right)} \quad (3)$$

where d is the discount rate (5%) [34], and i_F refers to the inflation rate considered for the annual fuel savings, $FS_{S\text{-}CCHP}$ (1.23%) [35]. To estimate the annual fuel savings, $FS_{S\text{-}CCHP}$, the total utility (electricity and natural gas) costs non incurred due to the electricity and thermal (SH and cooling) energy demand covered by the S-CCHP system are estimated, and the O&M costs of the system ($C_{O\&M}$), as well as the incomes for the electricity exported to the grid, are considered, as follows,

$$FS_{S-CCHP} = E_{cov} \cdot c_e + \frac{Q_{cov}}{\eta_{boiler}} \cdot c_e + E_{grid} \cdot FIT - C_{O\&M} \quad (4)$$

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 electricity price (0.145 €/kWh), c_{ng} is the natural gas price (0.057 €/kWh) and *FIT* is the current feed-in tariff applicable to this system (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 subscribed a 15-years heating service contract with the local 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 of about 0.11 €/kWh, which also includes the depreciation of investment costs incurred by the ESCO and system's maintenance. However, for the technoeconomic assessment of the S-CCHP system, only the avoided costs of the gas supply displaced by the proposed system are considered. The energy savings associated to the cooling demand covered are included in the electricity term, as currently this demand is satisfied by electricity-driven HVAC units, so the S-CCHP system will displace the corresponding electricity consumption. The *PBT* of the PV system is estimated using the same equations, although in this case there is no SH demand covered.

RESULTS

As mentioned previously, the limiting factor to size the S-CCHP system is the roof-space available in the Campus' buildings (23,600 m^2). For the PV system, the maximum PV installed power is 1.685 MW_p, which implies 8,827 m^2 of PV modules. For comparison purposes, the same installed power is considered for the proposed S-CCHP system, which corresponds to 7,020 PVT collectors with a total area of 10,846 m^2. Based on previous studies [36] and a preliminary analysis, the selected V_t/A_{cT} ratio for the storage tank volume is 50 L/m^2. The total number of PVT collectors is divided in 45 parallel S-CCHP systems which are assumed to be running in parallel, to facilitate O&M tasks, be able to run the systems according to the Campus needs, and limit the size of the different components (12 m^3 storage tank, 115 kW peak AbCH). Based on previous studies [24], a constant PVT collector flow-rate of 50 L/h is maintained.

Transient S-CCHP system results

This section presents detailed results obtained in TRNSYS on an hourly basis with the aim of understanding the performance of the proposed S-CCHP system. 9 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 demand) on the system's performance. Figures 3 and 4 show the results from the 21st to the 29th of January.

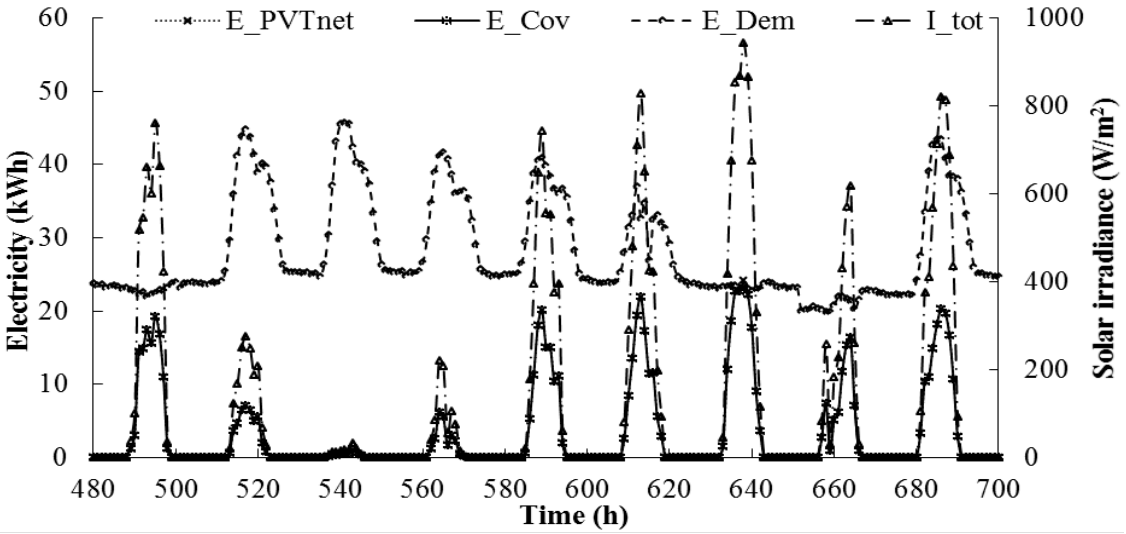

Figure 3. Electricity generated (E_{PVTnet}), electrical demand covered (E_{Cov}), electrical demand (E_{Dem}) and total solar irradiance at tilted angle (I_{tot}) for the S-CCHP system during 21-29 January

It is observed that the SH and electricity demands (dashed lines with diamonds) are much higher than the thermal and electrical energy generated by the PVT-based 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 line with triangles in Figure 3), more electricity and SH demand are covered (continuous lines with squares). On the 7th day (27th January), a small amount of electricity surplus (dotted lines with crosses) is exported to the grid. Figure 4 shows that the temperature at the top of the tank (dotted lines with triangles) considerably increases during the weekends (first two and last two days) 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.

Figure 5 shows the results from the 12th to the 20th of August. In this case, only the thermal energy results are shown as the electrical ones are equivalent to the ones obtained in winter (Figure 3). It is observed that, on the first and three last selected days, the temperature reached at the top of the tank (dotted lines with triangles) is not high enough to run the AbCH and to satisfy the cooling demand, so a large amount of auxiliary heat is needed (dashed-dotted line with crosses) to increase the temperature of the water entering the AbCH to 65°C (dashed-dotted line with pluses), required to start the unit. Conversely, in the rest of the days, more thermal energy is collected by the PVT collector array, leading to an increase in the storage tank water temperature (which reaches around 70°C in some hours of the day) and thus a reduction in the auxiliary energy required to heat the water that feeds the AbCH.

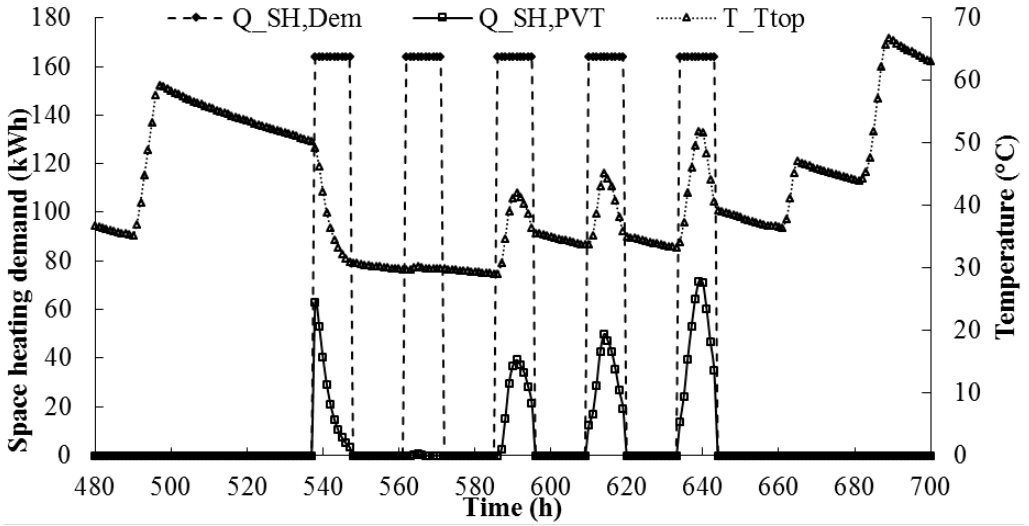

Figure 4. Total SH demand ($Q_{SH,Dem}$), SH demand covered ($Q_{SH,PVT}$), and water temperature at the top of the storage tank (T_{Ttop}) for the S-CCHP system during 21-29 January

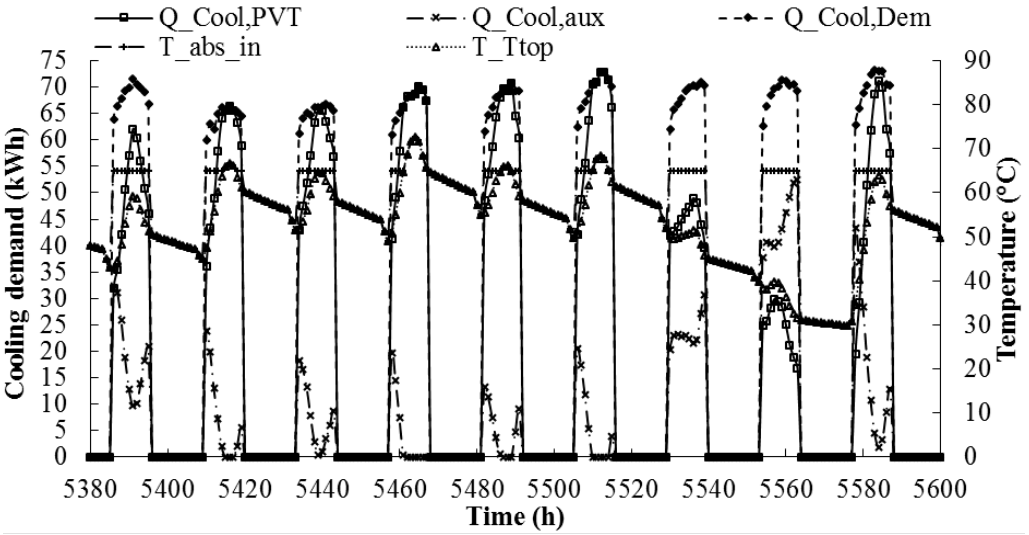

Figure 5. Thermal energy required by the AbCH ($Q_{Cool,Dem}$), thermal energy provided by the proposed S-CCHP system ($Q_{Cool,PVT}$) and auxiliary energy required ($Q_{Cool,aux}$) to satisfy the cooling demand for the S-CCHP system during 12-20 August

Technoeconomic assessment of the S-CCHP system

Table 1 shows the annual performance and economic results for the proposed S-CCHP system with three different sizes, as well as for the alternative PV system. With the S-CCHP system presented in the previous section (same installed power than the PV system, 1.685 MW_p) it is possible to cover 14% of SH, 66% of cooling and 17% of electricity demands of the University Campus of Bari. It should be noted that the percentage of onsite electricity consumption is very high (93% of the electricity generated by the PVT collectors is directly consumed), and the surplus electricity at any time step is injected into the grid in net metering option, hence withdrawn from the grid when demand exceeds solar generation. Considering also this net metering option, the electricity demand covered increases up to 19%. However, this influences the profitability of the investment, because the current electricity price (0.145 €/kWh) is applied to onsite consumed electricity, while a lower tariff (a *FIT* of 0.073 €/kWh) is applied to the excess electricity injected into the grid in net metering option. As discussed before, the limited amount of energy demand coverage is due to the restraint roof-space availability in the buildings.

Table 1. Energetic and economic results of different-sized PVT-based S-CCHP and PV systems

	S-CCHP system			PV system
Installed power (MW_p)	1.68	1.37	1.84	1.69
Installed area (m^2)	10,850	8,830	11,800	8,830
Total investment (C_0, M€)	5.28	4.65	5.59	1.60
SH demand covered (%)	14.0	11.6	15.0	-
Cooling demand covered (%)	65.8	57.4	69.4	-
Electricity demand covered (%)	17.4	14.8	18.5	20.6
Electricity demand covered with surplus (%)	18.7	15.4	20.4	22.3
Percentage of electricity generated fed into the grid (%)	7.3	4.0	9.0	7.7
Payback time (*PBT*, years)	19.3	20.6	18.9	6.5
Annual CO_2 emission reduction (tons CO_2/year)	1,170	980	1,260	780

The system payback time (*PBT*) is 19.3 years, which is considerable higher (3 times) than the *PBT* of the equivalent PV system (6.5 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 significantly lower (2.5 times) 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 down to 14.4 years. An incentive of the proposed S-CCHP system is the high potential CO_2 emission reduction (1,174 tons CO_2/year), which is 50% higher than for the PV system.

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 1 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. 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* (18.9 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 should be 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.

CONCLUSIONS

In this paper, the technoeconomic performance of a S-CCHP system based on a novel flat-box PVT collector is assessed for the provision of space heating (SH), cooling and electricity to the University Campus of Bari. The hourly energy demand profiles of the Campus are estimated based on the data provided by Campus managers, and used as inputs in the developed TRNSYS model. The model features the hybrid PVT collectors coupled via a thermal store with a single-effect LiBr-H_2O AbCH unit. The current gas-fired boilers are used as a backup heating system. Transient simulations are run in TRNSYS over a full year on an hourly basis, and the results are added up to obtain the annual energy generated and energy demand covered which are then used to estimate the system's *PBT* and potential CO_2 emission reduction.

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 14% 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 proposed AbCH,

with which 66% 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. 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 (19.3 years *vs*. 6.5 years). The much lower (2.5 times) price of natural gas compared to the electricity price also hinders the potential of the proposed S-CCHP system when this system is proposed to substitute current gas-fired boilers. In terms of potential CO_2 emission reduction, the results show that the proposed S-CCHP system has the potential to displace around 1,170 tons CO_2/year, which is 50% more than for the PV system.

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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