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ScienceDirect

Energy Procedia 158 (2019) 1229–1234

Energy Procedia

www.elsevier.com/locate/procedia

10th International Conference on Applied Energy (ICAE2018), 22-25 August 2018, Hong Kong, China

Thermoeconomic assessment of a PV/T combined heating and power system for University Sport Centre of Bari

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Abstract

This paper presents a thermoeconomic analysis of a solar combined heating and power (S-CHP) system based on hybrid photovoltaic-thermal (PV/T) collectors for the University Sport Centre (USC) of Bari, Italy. Hourly demand data for space heating, swimming pool heating, hot water and electricity provision as well as the local weather data are used as inputs to a transient model developed in TRNSYS. Economic performance is evaluated by considering the investment costs and the cost savings due to the reduced electricity and natural gas consumptions. The results show that 38.2% of the electricity demand can be satisfied by the PV/T S-CHP system based on an installation area of 4,000 m^2. The coverage increases to 81.3% if the excess electricity is fed to the grid. In addition, the system can cover 23.7% of the space heating demand and 53.8% of the demand for the swimming pool and hot water heating. A comparison with an equivalent gas-fired internal combustion engine (ICE) CHP system shows that the PV/T system has a longer payback time, i.e., 11.6 years *vs*. 3 years, but significantly outperforms the ICE solution in terms of CO_2 emission reduction, i.e., 435 tons CO_2/year *vs*. 164 tons CO_2/year. These findings suggest that even though the economic competitiveness of the proposed PV/T S-CHP system is not yet favourable when compared to the alternative gas-fired ICE-based system, the S-CHP solution has an excellent decarbonisation potential, and that if this is of importance in the wider sense of energy-system decarbonisation, it is necessary to consider how the higher upfront costs can be addressed.

Keywords: cogeneration; combined heat and power; CHP; hybrid collector; internal combustion engine; PV/thermal; PV/T; solar energy; sport centre

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10.1016/j.egypro.2019.01.312

1. Introduction

Renewable energy has surpassed fossil fuels as the main driver for global power capacity growth since 2015, currently accounting for >50% of new installations [1], with distributed solar [2] and in particular photovoltaic (PV) technology expected to continue to dominate market growth in the short term. Apart from power generation by PV panels, solar energy can be harvested effectively as heat via solar thermal technologies [3-5]. Hybrid PV-thermal (PV/T) collectors combine PV cells and solar thermal collectors into one integrated component, offering higher energy output than the side-by-side PV and solar thermal technologies as both heat and electricity are generated from the same aperture area.

Although the PV/T market is still small, PV/T-based systems have attracted an interest recently due to their good potential for covering the cooling, heating and power demands for buildings. Research on PV/T-water systems has been mainly focused on system modelling [6], thermal or optical performance improvement [7-9], system integration [10], as well as technoeconomic and environmental assessments in potential applications [11]. Most previous analyses on PV/T-water systems focussed on residential buildings [6,7,11,12]. Other types of buildings, such as commercial and public buildings which are considered as important application directions for PV/T systems but less studied, differ significantly from residential buildings in terms of available roof area and energy demand, thereby warrant further investigation.

This paper aims to investigate the thermoeconomic potential of a PV/T-based solar combined heating and power (S-CHP) system in the University Sport Centre (USC) of Bari, Italy, for covering the demands of swimming pool, hot water, space heating and electricity. Based on the thermoeconomic metrics obtained from an hourly transient model over a year, the PV/T S-CHP system is further compared to an internal combustion engine (ICE) CHP system, so as to assess the potentials and challenges of this renewable energy solution.

2. Methodology

A plan of the USC of Bari, Italy is shown in Fig. 1(a), with roof areas shadowed in red. The thermal demands of the swimming pool, hot water and space heating are currently covered by gas boilers with an annual consumption of about 175,000 Sm^3 of natural gas. The water delivery temperatures for the swimming pool and hot water are both 55 °C, while that for space heating is 70 °C. Apart from the thermal demands, the USC requires an annual electricity demand of 814 MWh. In order to reduce the dependency on natural gas for the USC, a PV/T-based S-CHP is proposed to cover the heating and power demands, as shown in Fig. 1(b). The thermal output of the PV/T-water collectors is stored in a water storage tank through a heat transfer loop. If there is thermal demand, the stored energy is extracted and upgraded to the required temperature by existing gas boilers if necessary. The electrical output of the PV/T collectors is used to cover the USC's electricity demand and the surplus is injected into the grid in net metering option, while electricity is withdrawn from the grid when demand exceeds solar generation.

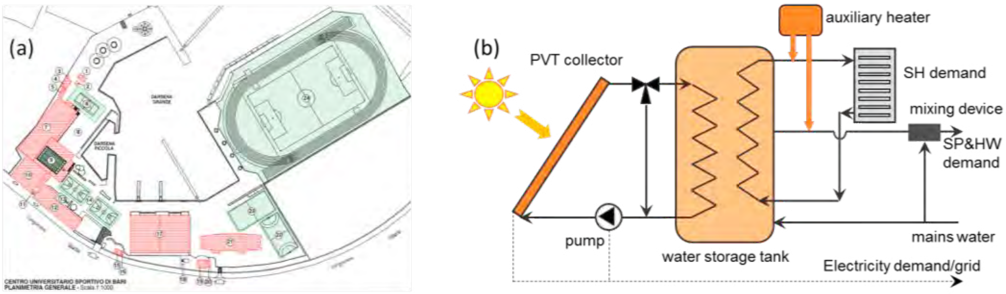

Fig. 1. (a) Plan of the USC of Bari with roof areas shadowed in red, and (b) schematic of a PV/T S-CHP system for the USC (SH: space heating; SP: swimming pool; HW: hot water).

The PV/T S-CHP system is modelled in TRNSYS software with hourly local weather and energy demand data as inputs. Quarter-hourly data are available for the total electricity demand of the USC, which are aggregated into hourly electricity consumption for the simulations. A flat profile from 8 am to 9 pm is assumed to estimate the space heating demand based on the available monthly gas consumption data. Similarly, a flat profile from 7 am to 9 pm is assumed for the thermal demand for the swimming pool. Hot water demand is required from 12 pm to 10 pm, with an assumed profile in accordance with the profile of users in the USC. Polycarbonate flat-box PV/T collectors, developed in previous research [7,13], are considered with a nominal electric power of 240 W_p, an electrical efficiency of 14.7% and a temperature coefficient of 0.45 %/K. These PV/T collectors are modelled by modifying model element Type 560 to match the thermal performance curve. An installation area of 4,000 m^2 is considered for the PV/T collectors, which is the maximum roof area available in the USC. A stratified water storage tank (Type 534) is used for thermal energy storage, with 6 nodes along its vertical axis. Hot water for space heating is extracted via a port at the top of the tank and returns to the lower part (Node 4) of the tank. To satisfy the thermal demand of swimming pool and hot water, which is at a lower temperature, water is extracted through a second port at the upper part (Node 2) of the tank and returned to a lower part (Node 4). In both streams, auxiliary gas boilers are used to heat up the water when the water temperatures are lower than the required ones. The total capacity of the water storage tanks is 200 m^3, considering parallel tanks, which corresponds to the typically value of 50 litre per unit area of PV/T collectors [14].

The economic performance of the PV/T S-CHP is assessed in terms of the payback time by considering the annual cost savings due to the reduced electricity and natural gas bills, together with the investment cost (C_0) and the operation and maintenance costs ($C_{\mathrm{O\&M}}$). The costs of the PV/T collectors [13], storage tank [15], pumps and fluids [13] are estimated by using correlations based on the existing market prices. The auxiliary heater cost is not included as the USC has gas-fired boilers. The payback time is calculated from,

$$PBT = \frac{\ln\left[\frac{C_0(i_{\mathrm{F}}-d)}{FS}+1\right]}{\ln\left(\frac{1+i_{\mathrm{F}}}{1+d}\right)}\,, \tag{1}$$

where d is the discount rate (taken as 5% [16]), and i_{F} refers to the inflation rate considered for the annual fuel savings (taken as 1.23% [17]). To estimate the annual fuel saving, *FS*, the total utility (electricity and natural gas) cost savings due to the electricity and thermal energy demand covered by the system are estimated as,

$$FS = E_{\mathrm{cov}} \cdot c_{\mathrm{e}} + E_{\mathrm{grid}} \cdot s_{\mathrm{e}} + \frac{Q_{\mathrm{cov}}}{\eta_{\mathrm{boiler}}} c_{\mathrm{ng}} - C_{\mathrm{O\&M}}\,, \tag{2}$$

where E_{cov} and Q_{cov} are the electrical and thermal demands covered by the system, E_{grid} the electricity provided to the grid via net metering, c_{e} and c_{ng} the electricity (0.205 €/kWh) and natural gas (0.0563 €/kWh) prices, η_{boiler} the boiler efficiency (85%), and s_{e} the electricity price for the net metering option applicable to the system (0.103 €/kWh). The utility price values correspond to current tariffs for the USC of Bari. The annual CO_2 emission reduction by the PV/T S-CHP system is also estimated based on the current CO_2 emission factors in Italy. The results are then compared to an ICE-CHP system.

3. Results and discussion

3.1. Transient operation

An hourly transient simulation is performed over a year for the PV/T S-CHP system to assess the thermoeconomic performance. Fig. 2 shows the electricity demand of the USC, the net electricity generated, once subtracted the water-pump consumption, and electricity covered by the PV/T S-CHP system in two representative periods of the year, i.e., 9 days in January and in August. It is observed that the system generates much more electricity than the USC demand at daytimes when solar irradiance is high. The excess electricity, which accounts for more than half of the total generation, is fed into the grid using the net metering option. When the generated electricity is not sufficient to cover all the demand at low or no solar irradiance conditions, electricity from the grid is used to fill the gap. As expected, more electricity is generated in August than that in January by the PV/T S-CHP system (due to high-irradiance and sunny days), which allows the system to cover most of the daytime demand.

The thermal demand, thermal output and auxiliary heating, as well as the required and delivered water temperatures for the swimming pool heating and hot water are shown in Fig. 3. The temperature of the outlet water from the water storage tank in the 21st – 29th of January is much lower than that in 10th – 17th of August (40-50 °C in most of the days *vs*. 80-90 °C), due to the lower solar irradiance in winter. Consequently, in winter auxiliary heating is required (blue dashed line in Fig. 3 (a)) to heat the water to the delivery set-point temperature (55 °C), while in summer the outlet tank temperature should be cooled down to the set-point temperature, no requiring any auxiliary heating. Thus, only a small amount of the thermal demand is covered by the PV/T S-CHP in January, while a 100% of the demand is satisfied in August. Solar thermal energy from the PV/T S-CHP system serves as the preheating source for swimming pool heating and hot water in most of the winter days, as shown in Fig. 3(a). As before, the water temperature supplied from the top of the water storage tank is lower than the space heating delivery temperature (70 °C), thus requiring auxiliary heating (blue dashed lines in Fig. 4). Still, the thermal output of the PV/T S-CHP system takes up a considerable amount of the demand through preheating the water (orange dashed lines in Fig. 4), from which the cost of natural gas consumption is reduced.

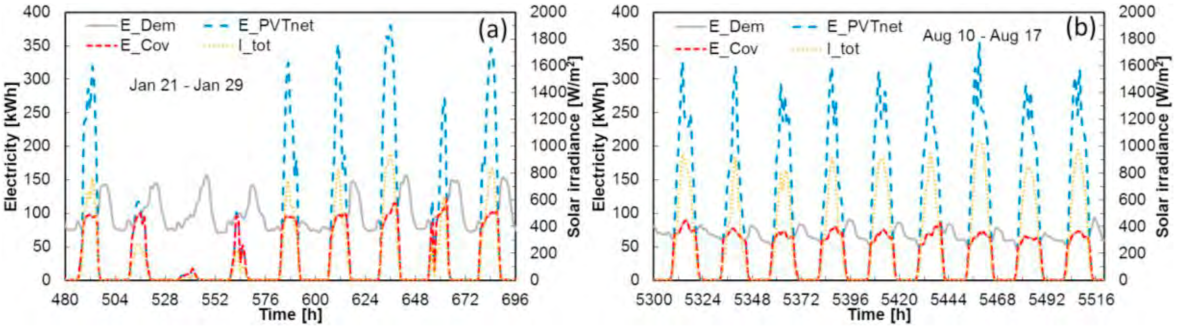

Fig. 2. Electricity demand (E_{Dem}), electricity generated ($E_{\mathrm{PV/Tnet}}$), electricity demand covered (E_{Cov}) and total solar irradiance at title angle (I_{tot}): (a) 21st – 29th Jan., and (b) 10th – 17th Aug.

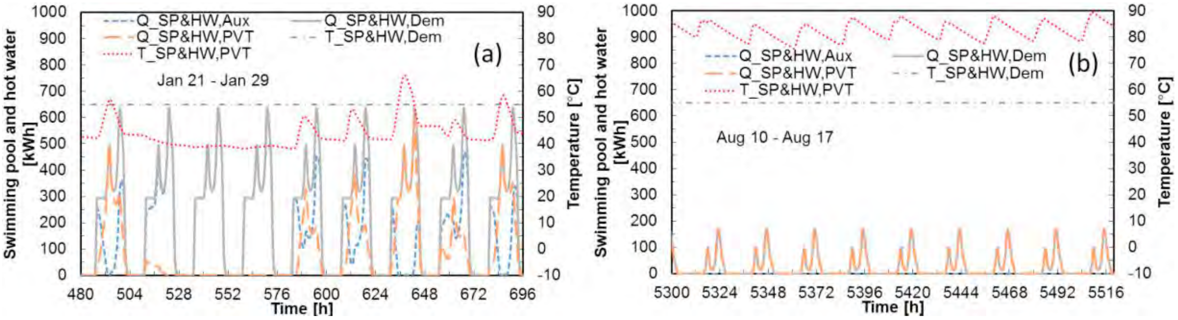

Fig. 3. Thermal energy demand ($Q_{\mathrm{SP\&HW,Dem}}$), thermal output of PV/T collectors ($Q_{\mathrm{SP\&HW,PV/T}}$), auxiliary heating ($Q_{\mathrm{SP\&HW,Aux}}$), required ($T_{\mathrm{SP\&HW,Dem}}$) and delivered ($T_{\mathrm{SP\&HW,PV/T}}$) water temperatures from the water tank for swimming pool and hot water: (a) 21st – 29th Jan., and (b) 10th – 17th Aug.

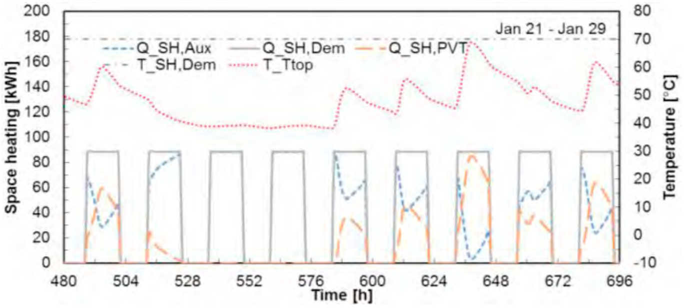

Fig. 4. Thermal demand ($Q_{\mathrm{SH,Dem}}$), thermal output of PV/T collectors ($Q_{\mathrm{SH,PV/T}}$), auxiliary heating ($Q_{\mathrm{SH,Aux}}$), required water temperature ($T_{\mathrm{SH,Dem}}$) and water temperature delivered from the water tank ($T_{\mathrm{SH,PV/T}}$) for space heating in 21st – 29th Jan.

3.2. Monthly results

Monthly results of the demand, generation, and demand coverage of the electricity, swimming pool heating and hot water, and space heating are shown in Fig. 5. It is found that the total electricity generation of the PV/T S-CHP system is about the same as the demand for half of a year when solar irradiance is high. However, due to the daily profiles of solar energy and electricity demand, only half of the total generated electricity is directly used in the USC, while the rest is exported to the grid. Auxiliary heating is the dominant source for swimming pool heating and hot water usage from November to March, whereas the solar heating covers most of the thermal demand in the rest of the months. In particular, the contribution of solar heating from June to September is up to 100%. As the space heating with a relatively high water temperature is required in winter, the thermal output of the PV/T S-CHP only covers a small amount of the thermal demand of the space heating, and it is mostly used for water preheating.

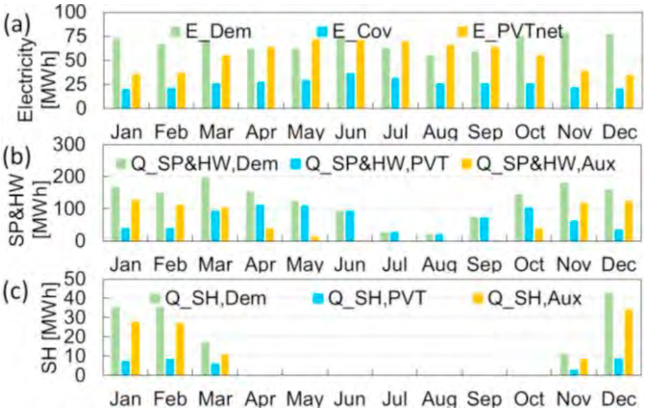

Fig. 5. (a) Monthly electricity demand (E_{Dem}), generation ($E_{\text{PV/Tnet}}$) and coverage (E_{Cov}), (b) monthly thermal demand ($Q_{\text{SP\&HW,Dem}}$), thermal energy covered by the PV/T S-CHP system ($Q_{\text{SP\&HW,PV/T}}$) and auxiliary heating ($Q_{\text{SP\&HW,Aux}}$) for swimming pool and hot water, (c) monthly thermal demand ($Q_{\text{SH,Dem}}$), thermal energy covered by the PV/T S-CHP system ($Q_{\text{SH,PV/T}}$) and auxiliary heating ($Q_{\text{SH,Aux}}$) for space heating.

3.3. Economic analysis and comparison with ICE-CHP system

Table 1 summarizes the annual energetic and economic results for the PV/T S-CHP system, as well as the results of an ICE-CHP system. The S-CHP system can cover 23.7% of the total annual space heating demand, plus 53.8% of the thermal demand of swimming pool and hot water. The total thermal demand of the USC covered by the PV/T S-CHP system is 51.2%. The electricity covered by the S-CHP system, defined as the percentage of the electricity demand instantly satisfied, is 38.2%. If the electricity injected to the grid is also included (as it is injected with the net-metering option), the total electricity demand covered increases up to 81.3%. However, the percentage of the instantaneous electricity covered influences the profitability of the investment, because the tariff for the electricity fed into the grid and withdrawn later on to fulfil the demand is only the generation cost component (i.e., 50%) of the total electricity tariff. In this case, the payback time (*PBT*) of the PV/T S-CHP system is 11.6 years.

Table 1. Energetic and economic results of PV/T S-CHP system and ICE-CHP system.

	PV/T S-CHP	**ICE-CHP**
Installed power (kW) (electrical/thermal power)	624 (electrical)	95 & 185 (electrical & thermal)
SH demand covered (%)	23.7%	-
SP&HW demand covered (%)	53.8%	-
Total thermal demand covered (%)	51.2%	82.9%
Electricity covered (%)	38.2%	83.1%
Total electricity supply (%)	81.3%	83.1%
Total investment (C_0, M€)	1.31	0.328
Payback time (*PBT*, year)	11.6	3.0
Annual CO_2 emission reduction (tons CO_2/year)	435	164

For comparison purposes, a gas-fired ICE-CHP system is also assessed. It is found that the ICE-CHP system covers much higher thermal and electricity demands, 82.9% and 83.1% respectively, with a lower investment cost, which results in a payback time of 3 years. The higher coverage of the electricity demand arises from the baseload electricity generation of the ICE, which allows an optimal match between electricity generation and demand. Although the total electricity generated by the PV/T S-CHP is similar to that generated by the ICE-CHP system, the mismatch between generation and demand in the former case affects the payback time. In this case, an electric storage system could introduce an electric load following capability for the PV/T S-CHP system, avoiding the net metering operation and increasing the revenues from avoided cost of electricity supply, but incurring in further investment costs for the storage system.

The CO_2 emission reduction of the PV/T S-CHP system is considerably higher than that of the ICE-CHP system, which would amongst other help meet the EU commitment of 40% carbon emission reductions by 2030. Further incentives from renewable electricity and heating, and from high efficiency CHP system, are available from the White Certificates mechanism as operated in the Italian energy framework, which provides a contribution up to 250

€/TOE (ton oil equivalent) saved. These support measures, that increase the profitability of both the investments here proposed, have not been considered in this preliminary assessment.

4. Conclusion

A S-CHP system has been studied for the provision of electricity, along with swimming pool, hot water and space heating in the USC of Bari, Italy. Transient modelling has been performed in TRNSYS over a year with hourly weather and demand data given as inputs. Excess electricity generated by the PV/T collectors is fed to the grid by using a net metering option. The current gas-fired boilers are used as a backup heating system if the thermal output of the S-CHP is not sufficient. The results show that the total electricity generated by the PV/T S-CHP system corresponds to 81.3% of the total electricity demand of the site, however, due to the temporal variability of the solar irradiance the instantaneous electricity generation covers only 38.2% of the real-time demand, while the rest is exported to the grid and imported later at a lower price. The S-CHP also covers 51.2% of the total thermal demand of the site, including 23.7% of the space heating demand and 53.8% of the demand for swimming pool heating and hot water. An ICE-CHP system fired by natural gas has also been assessed for comparison purposes. It is found that the PV/T S-CHP system has a longer payback time than the gas-fired ICE-CHP system, i.e., 11.6 years *vs.* 3 years, but has a much better CO_2 emission reduction performance, i.e., 435 tons CO_2/year *vs.* 164 tons CO_2/year. This work suggests that such PV/T S-CHP solutions have an excellent decarbonisation potential, and that further efforts relating to technology innovation and cost reduction are required before they can become economically competitive with conventional fossil-fuel solutions.

Acknowledgement

This work was supported by the UK Engineering and Physical Sciences Research Council (EPSRC) [grant number EP/M025012/1]. Data supporting this publication can be obtained on request from cep-lab@imperial.ac.uk.

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