Thermodynamic and Economic Assessments of a Hybrid PVT-ORC Combined Heating and Power System for Swimming Pools

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Abstract

The thermodynamic and economic performance of a solar combined heat and power (S-CHP) system based on an array of hybrid photovoltaic-thermal (PVT) collectors and an organic Rankine cycle (ORC) engine is considered for the provision of heating and power to swimming pool facilities. Priority is given to meeting the thermal demand of the swimming pool, in order to ensure a comfortable condition for swimmers in colder weather conditions, while excess thermal output from the collectors at higher temperatures is converted to electricity by the ORC engine in warmer weather conditions. The thermodynamic performance of this system and its dynamic characteristics are analysed on the basis of a transient thermodynamic model. Various heat losses and gains are considered in accordance to environmental and user-related factors for both indoor and outdoor swimming pools. A case study is then performed for the swimming pool at the University Sport Centre (USC) of Bari, Italy. The results show that employing a zeotropic mixture of R245fa/R227ea (30/70%) as the ORC working fluid allows such an ORC system to generate ~50% more power than when using pure R236ea due to the better temperature match of the cycle to the low-temperature hot-water heat source from the output of the PVT collectors. Apart from generating electricity, the ORC engine also alleviates PVT collector overheating, and reduces the required size of the hot-water storage tank. With an installation of 2000 m^2 of PVT collectors, energetic analyses indicate that the proposed S-CHP system can cover 84-96% of the thermal demand of the swimming pool during the warm summer months and 61% of its annually integrated total thermal demand. In addition, the system produces a combined (from the collectors and ORC engine) of 328 MWh of electricity per year, corresponding to 36% of the total electricity demand of the USC, with ~4% coming from the ORC engine. The analysis suggests a minimum payback time of 12.7 years with an optimized tank volume of 125 m^3.

Keywords: organic Rankine cycle, ORC, PV-thermal, PVT, solar energy, swimming pool.

Introduction

Hybrid PV-thermal (PVT) collectors have attracted interest recently due to their potentially improved electrical efficiency over single PV panels if operated suitably, their ability to provide an additional thermal energy output and the flexibility they allow for further integration with other technologies, including thermal energy storage options. Many different hybrid PVT-based systems have been investigated for various purposes, such as PVT-water systems for domestic heating (hot water, space heating) and power provision [1-3]; here, we extend the capabilities of these systems by including a low-temperature heat-driven thermodynamic cycle [4,5].

Considering the potential of hybrid PVT systems for combined heating and power (CHP), the aim of this work is to assess the energetic and economic feasibility of hybrid PVT technology when applied to swimming pool applications. The majority of previous studies found on solar swimming pool heating focus on solar-thermal collector heating systems [6,7] or solar-assisted heat-pump heating systems with conventional solar-thermal collectors [8,9]; far less effort has been devoted to the employment of hybrid PVT collectors in solar-CHP (S-CHP) systems for meeting the heating and power demands of swimming pools. To the authors' knowledge, only one study has considered a heating system based on PVT technology for a swimming pool, located in Naples, Italy [10]. Results from transient simulations and sensitivity analyses performed with TRNSYS software showed that the system considered in this study was not profitable without public funding policies and became viable only after introducing thermal feed-in tariffs due to the high collector costs. However, solar irradiation and thermohygrometric conditions are highly geographically dependent, so the energetic/economic performance of such PVT-based S-CHP systems will differ significantly at different locations, and depends strongly on system configuration and operational strategies, which merits further investigation.

This paper presents a solar-driven PVT-ORC S-CHP system for swimming pool facilities. An ORC engine converts the excess thermal output of the PVT collector array into (secondary) electrical power when the heating demand for the swimming pool is low, which helps to improve the overall system efficiency and prevent overheating of the collectors. The potential of the system for a swimming pool application at the University Sport Centre (USC) of Bari, Italy, is assessed in terms of both thermodynamic and thermoeconomic performance metrics.

System configuration and modelling methodology

Swimming pool facilities have a heavy thermal demand, and gas boilers are typically used for heating. Figure 1 shows a simplified schematic of the proposed PVT-ORC S-CHP system for the swimming pool application. A hot water storage tank stores thermal energy produced from the PVT-water collectors. The system is designed to prioritise meeting the heat demand of the swimming pool, while the excess thermal output from the collectors is recovered and converted by the ORC engine for generating additional electricity. Due to fluctuations of solar radiation, an auxiliary heating, i.e. gas boiler, is always necessary as the backup heating source.

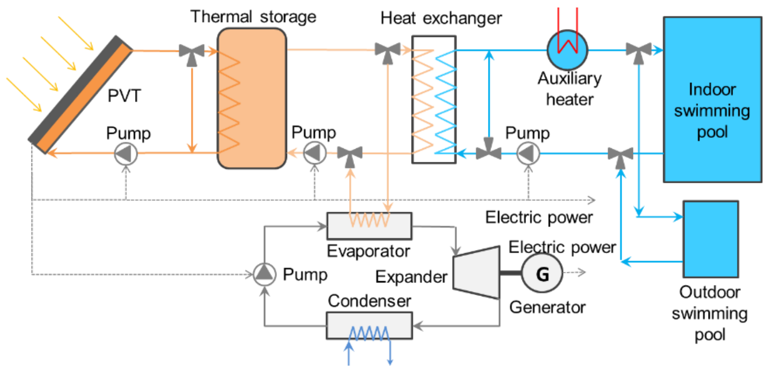

Figure 1. Simplified schematic of PVT-ORC S-CHP system for swimming pool application.

Both indoor and outdoor swimming pools are considered in the present study. A swimming pool model is built by considering various energy transfer mechanisms. Thermal demand ($\dot{Q}_{\mathrm{sp}}$) of the swimming pools is calculated from the thermal balance between heat gains and losses, including solar heat absorption ($\dot{Q}_{\mathrm{sol}}$), heat generation from swimmers ($\dot{Q}_{\mathrm{occ}}$), convection heat loss to air ($\dot{Q}_{\mathrm{conv}}$), conduction heat loss to soil ($\dot{Q}_{\mathrm{cond}}$), water evaporation heat loss ($\dot{Q}_{\mathrm{evap}}$), radiation loss to surroundings ($\dot{Q}_{\mathrm{rad}}$), and heat loss from refilling water ($\dot{Q}_{\mathrm{fill}}$). The equations for the above energy transfer mechanisms are summarized below:

$$\dot{Q}_{\mathrm{sol}} = \alpha G A_{\mathrm{sp}} \tag{1}$$

$$\dot{Q}_{\mathrm{occ}} = N_{\mathrm{occ}} \dot{q}_{\mathrm{occ}} \tag{2}$$

$$\dot{Q}_{\mathrm{conv}} = h A_{\mathrm{sp}} (T_{\mathrm{sp}} - T_{\mathrm{a}}) \tag{3}$$

$$\dot{Q}_{\mathrm{cond}} = q_{\mathrm{ss}}^{*} k_{\mathrm{soil}} h A_{\mathrm{sp}} (T_{\mathrm{sp}} - T_{\mathrm{soil}})/L_{\mathrm{c}} \tag{4}$$

$$\dot{Q}_{\mathrm{evap}} = \dot{m}_{\mathrm{evap}} L_{\mathrm{w}} A_{\mathrm{sp}} \tag{5}$$

$$\dot{Q}_{\mathrm{rad}} = \varepsilon A_{\mathrm{sp}} \sigma (T_{\mathrm{sp}}^4 - T_{\mathrm{sur}}^4) \tag{6}$$

$$\dot{Q}_{\mathrm{fill}} = \dot{m}_{\mathrm{fill}} c_{\mathrm{p}} (T_{\mathrm{sp}} - T_{\mathrm{w}}) \tag{7}$$

$$\dot{Q}_{\mathrm{sp}} = \dot{Q}_{\mathrm{conv}} + \dot{Q}_{\mathrm{cond}} + \dot{Q}_{\mathrm{evap}} + \dot{Q}_{\mathrm{rad}} + \dot{Q}_{\mathrm{fill}} - \dot{Q}_{\mathrm{occ}} - \dot{Q}_{\mathrm{sol}} \tag{8}$$

Solar radiation ($\dot{Q}_{\mathrm{sol}}$) is only necessary in the outdoor swimming pool, and the absorption coefficient α is chosen as 0.85 [10]. For the heat generation ($\dot{Q}_{\mathrm{occ}}$) from swimmers, a constant rate ($\dot{q}_{\mathrm{occ}}$) of 200 W per user is assumed. Heat transfer coefficient (h) for the convection loss ($\dot{Q}_{\mathrm{conv}}$) of the indoor swimming pool is calculated from the natural convection equation across a horizontal plate [11], while forced convection due to wind effect is considered for the outdoor pool [7]. The thermal conduction to ground ($\dot{Q}_{\mathrm{cond}}$) is evaluated by taking into account the shape effect of swimming pools via a dimensionless conduction rate (q_{ss}^*) and a characteristic length (L_{c}) [11]. A constant soil temperature (T_{soil}) of 12 ℃ is assumed here. Water evaporation causes the main heat loss in swimming pools. The evaporation rate ($\dot{m}_{\mathrm{evap}}$) is mainly affected by the vapour partial pressure, number of users and wind speed. An empirical model presented by Shah [12,13], which was validated against experimental data, is adopted. Radiation occurs due to the temperature differences between the swimming pools (T_{sp}) and its surroundings (T_{sur}). The surrounding temperature is the sky temperature for outdoor swimming pool, while it is a weighted value between room and outdoor temperatures for indoor swimming pool. In both swimming pools, an emissivity (ε) of 0.9 is assumed [10]. The evaporation and presence of users cause a reduction of the pool water volume. A refilling water flow is necessary to maintain the water level and ensure the water quality. A constant refilling water flow rate ($\dot{m}_{\mathrm{fill}}$), which enables a daily refreshment of 5% of the total pool volume, is assumed in the model.

When the thermal demand of the swimming pool is low and the water temperature exceeds the predefined deadband temperature, excess heat is delivered to the ORC engine to generate electricity. The ORC engine is sized according to the difference between the thermal energy gained at the PVT-water collectors and the swimming pool demand. A subcritical non-regenerative ORC is considered. The temperature difference between the hot water inlet and the ORC working fluid outlet (expander inlet) is taken as 5 ℃ [14], and a fixed pinch temperature difference of 5 ℃ is assumed. The evaporation and condensation pressures are then determined to ensure that the pinch temperature condition is met under the constraints of the deadband operating temperature (70 ℃) and mains water temperature. The isentropic efficiencies of the pump and the expander are both set to 0.8. The electrical conversion efficiencies of the pump and the expander are assumed as 0.9. Selection of an appropriate working fluid is important for the cycle efficiency. A range of pure working fluids, including R123, R227ea, R236ea, R245ca, R245fa and butane, are screened and R236ea is finally chosen due to its superior performance. As shown in Figure 2, the cycle performance with pure working fluid is limited due to the small temperature difference available from the heat source and sink. Zeotropic mixtures have a temperature slip phenomenon in evaporation and condensation processes, which enables a better matching with the temperature profiles of the heat source and sink, and helps to improve the output performance. Binary zeotropic mixtures including R245fa/R227ea, R245fa/RC318, R245fa/butane, R245fa/R152a and R245fa/R123, which have been studied for low-temperature ORCs [15], are considered for the proposed system. The R245fa/R227ea pair with a mass fraction of 0.3/0.7 is finally selected based on the comparisons of the cycle performance.

The swimming pool and ORC engine models are both implemented in MATLAB, and integrated with the component models of the PVT collector, water tank and other auxiliary facilities to form a dynamic system model in TRNSYS software environment. The PVT collector and water tank are modelled using Type 560 and Type 534 in TRNSYS. If water temperature at the top of the water tank is higher than 45 ℃ and there is a thermal demand of the swimming pool, the heat transfer fluid is pumped out of the tank to the swimming pool heat exchanger. If the water temperature exceeds 70 ℃ and the thermal output of PVT collectors exceeds the thermal demand of the swimming pool (i.e. the auxiliary heating is not required), the ORC engine is utilized. In this way, excess heat at relatively high temperatures is recovered, thus reducing the risk of overheating the collectors and simultaneously generating a useful (secondary) electrical output.

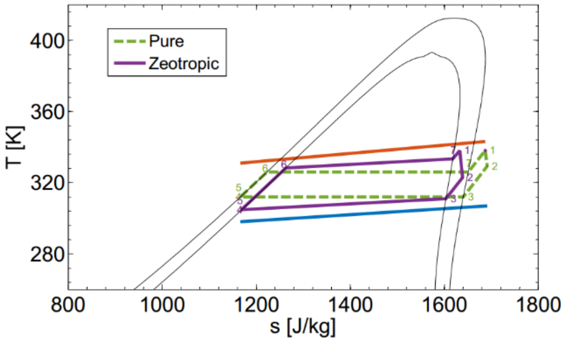

Figure 2. *T-s* diagrams of ORC cycle with pure working fluid (R236ea) and zeotropic mixture as working fluid (0.3R245fa/0.7R227ea).

A commercial flat-plate PVT collector [16] with a nominal electric power of 240 W and PV module efficiency of 14.1% is used for the simulation. The temperature coefficient of PV module is assumed to be –0.45 %/K. The collector has the following thermal performance,

$$\eta_{\text{th}} = 0.69 - 2.59T_{\text{r}} - 0.012GT_{\text{r}}^2 \tag{9}$$

where η_{th} is the thermal efficiency, T_{r} the reduced temperature and G the incident irradiance.

The investment costs (C_0) of the system are mainly associated with the PVT collectors, storage tank, ORC engine, pumps, fluids and installation costs. The storage tank cost is estimated using a correlation based on market prices of existing tanks across a range of storage volumes [17] and the other costs are estimated from the cost models described in Refs. [18,19]. The costs for the auxiliary heater and the water pump at swimming pool side are not considered as they are already installed in an existing swimming pool system. Thermoeconomic analyses are performed in terms of payback time (*PBT*), which is defined as the period of time required to recover the investment of the PVT-ORC S-CHP system. The payback time is calculated by,

$$PBT = \frac{\ln\left[\frac{C_0(i_{\text{F}}-d)}{FS}+1\right]}{\ln\left(\frac{1+i_{\text{F}}}{1+d}\right)} \tag{10}$$

where d is the discount rate (taken as 5% [20]), and i_{F} refers to the inflation rate considered for the annual fuel savings (taken as 1.23%) [21]. To estimate the annual fuel savings, *FS*, the total utility (electricity and natural gas) cost not incurred due to the electricity and thermal energy demand covered by the system is estimated, as follows,

$$FS = E_{\text{cov}} \cdot c_{\text{e}} + \frac{Q}{\eta_{\text{b}}} c_{\text{ng}} - C_{\text{O\&M}} \tag{11}$$

where E_{cov} and Q_{cov} are the electrical and thermal demands covered by the system, c_{e} is the electricity (0.145 €/kWh) and c_{ng} the natural gas (0.057 €/kWh) price, and η_{b} is the efficiency of the boiler. The utility price values correspond to the current tariffs for the USC of Bari.

Results and discussion

A PVT-ORC combined heating and power system case study is performed for the swimming pool application at the USC of Bari, Italy. The USC has an Olympic indoor swimming pool (50 m) and an outdoor swimming pool (25 m). The outdoor pool is only operated from July to September, and the indoor one is operated in the remaining months during which the thermal demand is met by a natural gas boiler with an efficiency of 85%. The swimming pool has about 95000 users per year. The hourly weather and user data of the university swimming pools over a whole year are given as the inputs to the model. Based on preliminary estimations of the solar radiation in Bari and the thermal demand for the swimming pools, a total installation area of 2000 m^2 is considered for the PVT collectors in the modelling, which covers about half of the roof area of the nearby buildings at the USC. A large water tank is needed due to the large continuous thermal demand, thus a volume from 50 m^3 to 175 m^3 is considered [10].

The comparisons of the energetic and economic performance of the PVT-ORC S-CHP system with the pure and zeotropic mixture working fluids, when the water tank volume is 100 m^3, are shown in Table 1. The electricity generated by the ORC engine increases by 50.6%, from 7.9 MWh to 11.9 MWh, when the R245fa/R227ea mixture is used instead of R236ea as the ORC working fluid. The efficiency of the ORC engine increases from 2.79% to 4.21%. This generated electricity corresponds to 3.60% and 2.42% of the total electricity output, respectively. As shown in Table 1, the payback time is smaller when the zeotropic working fluid is used, thus the results analysed below are all based on this fluid.

Table 1. Energetic and economic performance with pure (R236ea) and zeotropic mixture working fluid (0.3R245fa/0.7R227ea).

	R236ea	0.3R245fa/0.7R227ea
E_{orc} [MWh/yr]	7.9	11.9
E_{pvt} [MWh/yr]	318.8	318. 8
E_{orc} / (E_{pvt}+ E_{orc})	2.42%	3.60%
η_{orc}	2.79%	4.21%
PBT [yr]	13.1	12.8

The water tank is sized based on the energetic and economic performance. As shown in Figure 3, the thermal demand covered by the S-CHP system increases and the auxiliary thermal energy decreases, although progressively less so, at larger tank sizes. The generated electricity is almost independent of the tank volume. The *PBT* reaches a minimum at a tank volume of 125 m^3, with which a payback time of 12.7 years is estimated. It should be noted that incentives available for renewable energy generation have not been included in this analysis, but are expected to reduce significantly the system's payback time. Since the payback times with the tank volumes of 100m^3 and 125 m^3 are almost the same, the size of the water tank is selected as 100 m^3.

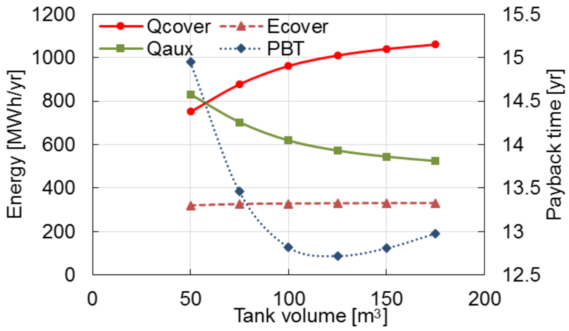

Figure 3. Effect of water tank volume on energetic and economic performance.

Hourly transient simulations are performed over a whole year. The evolutions of the thermal powers of different heat transfer mechanisms for the indoor and outdoor swimming pools are shown in Figure 4. Due to the differences in the surrounded environmental conditions, including wind speed, solar radiation and air temperature, the thermal demand of the indoor swimming pool is much more stable than that of the outdoor pool. The thermal demand of the outdoor pool drops to nearly zero when the solar irradiation is high. In any case, the evaporation loss is always the main contribution of the thermal demand, and it is highly dependent on the number of users.

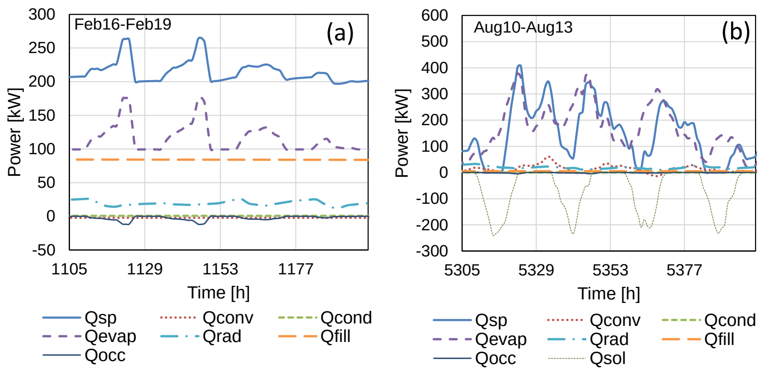

Figure 4. Transient thermal power evolutions for swimming pool: (a) indoor swimming pool, and (b) outdoor swimming pool.

The temperature variations and the pump control signals are shown in Figure 5. When the outlet water temperature of the PVT collectors is higher than the temperature in the water tank, the fluid circulating pump for the PVT collectors starts up to heat the water in the tank. The pump for the swimming pool operates when there is a thermal demand and the water temperature at the top of the tank is higher than the deadband temperature, i.e. 45 ℃. Once the top tank water temperature drops below 45 ℃, the swimming pool pump stops and the auxiliary heater works to meet the thermal demand. The pump for the ORC engine starts to deliver hot water to the evaporator to generate electricity when the water temperature at the top of the tank exceeds 70 ℃. As shown in Figure 5(a), the ORC engine does not work at cold weathers when the water temperature is low. It works occasionally at summer time when water temperature is sufficiently high, as shown in Figure 5(b).

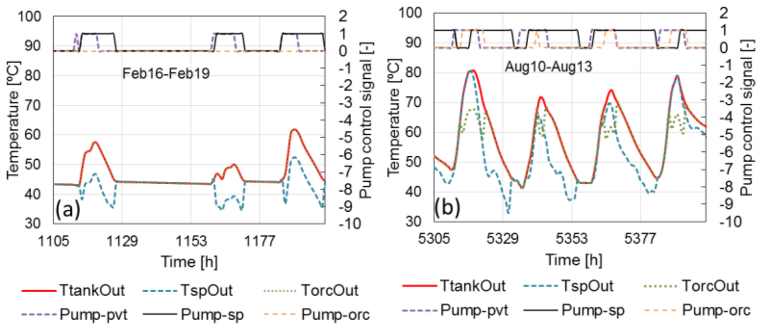

Figure 5. Temperatures and pump on/off control signals: (a) indoor, and (b) outdoor swimming pools.

Figure 6 shows the monthly thermal energy and electricity of the PVT-ORC S-CHP system. The PVT collectors cover most of the thermal demand at warm seasons, while the rest is met by the auxiliary gas boiler. The coverage percentage from the solar heating is at the range of 84%-96% from May to August. The relatively high-temperature thermal energy at summer times is partially delivered to the ORC engine for electricity generation, which reduces the coverage percentage. As shown in Figure 6(b), the PVT collectors produce the majority of the electricity due to the instinct low-efficiency of the ORC engine operated at hot water temperatures. A further comparison study on a PVT-only system without the ORC engine shows that the water temperature easily exceeds 100 ℃ in summertime, and a significantly larger tank (more than 3 times the current 100 m^3) is required to prevent the overheating. Therefore, although the presence of the ORC engine reduces the coverage percentage of the thermal demand at summer times, it also acts as an effective measure to prevent PVT collectors from overheating, with the extra benefit of generating electricity. Besides, a considerably smaller tank can be used, which is more feasible for a practical application due to space limitations and commercial products available on the market. With the proposed PVT-ORC S-CHP system, the solar heat covers 61% of the total thermal demand for the swimming pool within the whole year, with an electricity supply of 328 MWh, which covers 36% of the total electricity demand of the entire USC.

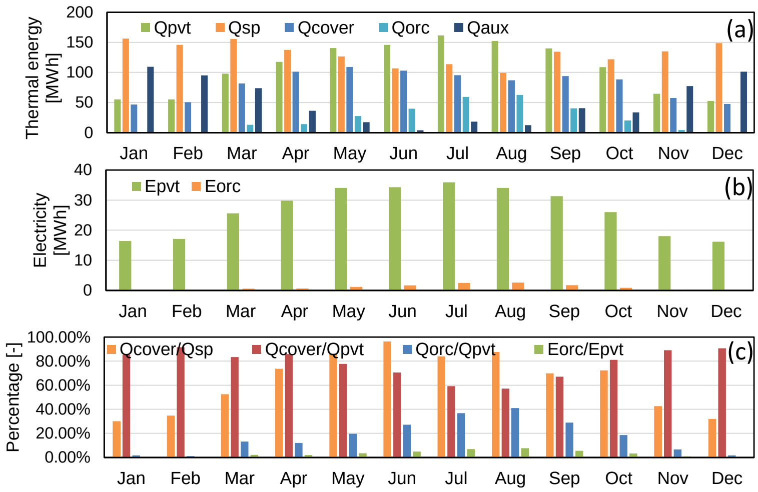

Figure 6. (a) Monthly thermal energy production and consumption, (b) monthly electricity production, and (c) their ratios.

Conclusions

A S-CHP system for a swimming pool facility based on the integration of a hybrid PVT collector array and an ORC engine has been studied. The thermal energy (i.e. hot water) output of the PVT-water collectors was used primarily to meet the thermal demand of the swimming pool, while excess heat at relatively high temperatures (> 70 ℃) was recovered by the ORC engine to generate secondary electricity in addition to the electrical energy output of the PVT collectors. A transient model was defined in the TRNSYS modelling environment. The thermal demands of both indoor and outdoor swimming pools were simulated by considering various heat transfer mechanisms in accordance to relevant environmental and user-related factors. In order to maximize the performance of the ORC engine in this low-temperature application, pure R236ea and the zeotropic mixture R245fa/R227ea (30/70%) were selected for further consideration, following a screening exercise of a range of working fluids. A case study was then performed for the swimming pool at the University Sports Centre (USC) in Bari, Italy. The results show that the ORC system with the zeotropic mixture outperforms the one with the pure fluid in terms of both energetic (by 50%) and economic indicators. With a total installation area of 2000 m^2, the system covers 61% of the annual thermal demands of the swimming pools, and generates a total of 328 MWh of electricity. The coverage percentage ranges from 84% to 96% in summer months. The electricity generated by the ORC engine corresponds to ~4% of the total electricity output of the system. An optimized water tank volume of 125 m^3 showed that a minimum payback time of 12.7 years can be expected for the proposed PVT-ORC S-CHP system in this case.

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