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A novel solar-assisted heat pump driven by photovoltaic/thermal collectors: Dynamic simulation and thermoeconomic optimization

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ABSTRACT

This paper presents a dynamic simulation model and a thermo-economic analysis of a novel polygeneration system based on a solar-assisted heat pump and an adsorption chiller, both driven by PVT (photovoltaic/thermal) collectors. The aim of this work is to design and dynamically simulate a novel ultra-high efficient solar heating and cooling system. The overall plant layout is designed to supply electricity, space heating and cooling and domestic hot water for a small residential building. The system combines solar cooling, solar-assisted heat pump and photovoltaic/thermal collector technologies in a novel solar polygeneration system. In fact, the polygeneration system is based on a PVT solar field, coupled with a water-to-water electric heat pump or to an adsorption chiller. PVT collectors simultaneously produce electricity and thermal energy. During the winter, hot water produced by PVT collectors primarily supplies the evaporator of the heat pump, whereas in summer, solar energy supplies an adsorption chiller providing the required space cooling. All year long, solar thermal energy in excess is converted into DHW (domestic hot water). The system model was developed in TRNSYS environment. 1-year dynamic simulations are performed for different case studies in various weather conditions. The results are analysed on different time bases presenting energetic, environmental and economic performance data. Finally, a sensitivity analysis and a thermoeconomic optimization were performed, in order to determine the set of system design/control parameters that minimize the simple pay-back period. The results showed a total energy efficiency of the PVT of 49%, a heat pump yearly coefficient of performance for heating mode above 4 and a coefficient of performance of the adsorption chiller of 0.55. Finally, it is also concluded that system performance is highly sensitive to the PVT field area. The system is profitable when a capital investment subsidy of 50% is considered.

1. Introduction

In the past decades, a number of Countries, especially in EU, massively supported conventional solar technologies (solar thermal and solar photovoltaic) by public funding [1]. This resulted in a significant reduction of their capital cost, especially for PV (photovoltaic) systems (from 7.0 k€/kWp to 1.3 k€/kWp). Simultaneously, more and more attention has been paid to some innovative solar technologies other than PV and solar thermal, namely: solar power [2,3], solar heating and cooling [4,5], hybrid PVT (photovoltaic/thermal) solar collectors [6–9]. The majority of these novel solar technologies are implemented in the novel solar polygeneration [10,11] system included in this paper. In the followings, a brief description of such technologies is provided.

PVT (photovoltaic/thermal) collectors are particularly promising, since they combine in a single component conventional photovoltaic collectors, PV, and conventional thermal SC (solar collectors) [12,13]. PVT collectors simultaneously produce electricity and heat [14]. PVT collectors are typically manufactured by covering the absorber of a conventional thermal collector with a suitable PV layer. Thermal energy is distributed to a fluid (typically air [15] or water [16–18]), whereas the PV layer produces electricity [12,13]. The overall result is the simultaneous production of electricity and heat [19]. In addition, the electrical efficiency of a PVT collector may be even higher than that of a conventional PV module, at least in case of low PVT operating temperatures [12,13,20]. The most common PVT configuration is the “sheet-and-tube” [21], where a conventional SC thermal collector is equipped

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with a PV layer encapsulated in the absorber, although several alternative configurations are currently under investigation [12,13,22,23]. PVT electrical efficiency decreases when the operating temperature increases. Usually, the performance drop-off due to temperature increase is not too high: it is typically around 0.45%/K for silicon cells [20], and even lower in case of novel PV materials, such as multi-junction solar cells which can approach a nominal efficiency of 40% [24,25]. In any case, a lower operating temperature of PVT collectors obviously leads to an improvement of both electrical and thermal efficiencies [26]. For this reason, PVT systems are typically used for low-temperature applications, such as domestic hot water production, floor heating, desiccant cooling [27,28]. A possible alternative for increasing the outlet temperature of the working fluid without decreasing the PVT electrical efficiency may consist in the use of a heat pump (mainly driven by the PVT electric output) [12,13,22].

The combination of PVT collectors and heat pumps is a special case of the category of the SAHP (solar-assisted heat pumps), in which solar thermal energy is used to enhance the COP (coefficient of performance) of a conventional HP (heat pump) providing space heating during the winter season [29,30]. SAHP typically include conventional flat-plate solar thermal collectors producing a hot fluid supplying heat to the evaporator of an electric vapor-compression heat pump. When SAHP system include PVT collectors, the compressor of the HP can be driven by the renewable electrical energy produced by the collectors, further enhancing the overall efficiency of the system [31]. SAHP systems are typically classified into two groups: direct and indirect coupled. In the first case, the refrigerant directly flows inside the PVT collectors. In the second case, PVT and HP working fluids are decoupled by means of a heat exchanger. Higher conversion efficiencies and lower capital costs are achieved by the direct configuration. Conversely, the indirect one is much more simple and flexible, especially during the summer season [32,33]. The majority of the studies available in literature only analyse the conventional direct SAHP arrangement based on an electric heat pump and flat-plate solar collectors. The combination with PVT systems is scarcely analyzed. In particular, Gorozable Chata et al. [32] investigated the thermal performance of a direct expansion solar-assisted heat pump with several refrigerants, using two different configurations for the collector, bare and with cover. The results showed that R-12 produces the highest value of COP, followed by R-22 and R-134A. A similar study was presented by Zhang et al. [34], who investigated the effects of the refrigerant charge on the performance of the system. In the optimum configuration, good system performance and feasible costs can be achieved [34]. Tagliafico et al. [35] proposed to use solar thermal collectors as thermal exchange units (evaporators) in a heat pump system, in order to improve the efficiency and the economic profitability of the system. The authors used a simplified approach and they found results consistent with those available in literature, with a mean primary energy saving of about 50% with respect to a standard gas burner. A similar approach was also used by Scarpa et al. [36], using a model developed around the fluid-independent Carnot cycle. The system produces hot sanitary water and it is equipped with an auxiliary gas burner. The authors found results in accordance with those available in the literature [36]. The direct expansion SAHP, including solar thermal collectors, was also investigated by Chow et al. [37]. The authors presented a numerical model of the system. Then, a simulation was performed using the TMY (typical meteorological year) weather data of Hong Kong: a year average COP (coefficient of performance) of 6.46 was found. A more complex direct SAHP was presented by Chaturvedi et al. [38], including a double-stage compression for high temperature applications. Results are presented and compared with those of a single-stage direct expansion solar-assisted heat pump. The authors concluded that significant improvement of the thermal performance is achieved at high condensing temperatures when using the double-stage SAHP system. However, a higher capital cost (due to the larger solar field area) must be taken into account. A more comprehensive analysis of the papers available in literature investigating direct SAHP system was presented by Kara et al. [39], also including energy and exergy models. From this study, it is clear that only a couple of papers investigate PVT collectors, whereas the remaining ones focus on conventional solar thermal collectors [39]. One of the few studies investigating SAHP including PVT collectors was presented by Chow et al. [40]. The authors modeled a PV-SAHP (photovoltaic-integrated solar heat pump) system, using a dynamic simulation model and the TMY weather data of Hong Kong. It was found that the proposed system with R-134a is able to achieve a year average COP of 5.93 and a PV efficiency of 12.1%; the energy output is therefore considerably higher than that of a conventional heat pump plus PV “side-by-side” system. The indirect SAHP configuration was investigated by Sterling et al. [41]. The authors designed and modeled an indirect SAHP for DHW (domestic hot water) production, which was compared to a conventional SDHW (solar domestic hot water) system and to an electric domestic hot water system. The simulations were performed by TRNSYS software, using a simple scheme and basic control strategies. It was found that the best performance, considering the electrical consumption and the operating cost, was achieved by the SAHP system. In this study, a solar field equipped with conventional solar thermal collectors was considered [41]. An indirect SAHP configuration also including PVT collectors was recently presented by Hazi and Hazi [33]. The authors presented a comparative study of indirect photovoltaic thermal solar-assisted heat pump systems for water heating in industry is presented. Both steam ejector heat pumps and mechanical compression heat pumps were evaluated, for an application in a paper mill. A numerical model was implemented including energy, exergy and economic balances for a Romanian climatic condition. The authors concluded that in winter the operation time of the heat pump is shorter than the duration of the solar radiation, while in summer, when the air temperature and the solar radiation are higher, such operation time equals the duration of the solar radiation. SAHP systems are also studied in a plurality of applications, such as: swimming pools [42,43], solar heating and cooling [21], desalination [44], geothermal heat pumps [45], etc. A considerable number of studies are also available in literature presenting different experimental analyses of different SAHP configurations [46–54], including a number of different solar devices (flat-plate collectors, PVT collectors, evacuate tube collectors, variable speed compressors, etc). All the papers investigating the experimental performance of SAHP systems are based on small systems, and mainly focus on the direct configuration arrangement.

As mentioned before, SAHP systems are specialized in the conversion of solar heat space heating energy during the winter season. Conversely, in summer, solar energy can be converted in space cooling energy by solar cooling systems [55,56]. In particular, this technology is particularly promising since the availability of solar radiation is simultaneous with building space cooling demand. Conversely, in winter time, the maximum heating demand often occurs in case of extremely scarce solar radiation [57]. The basic principle is simple since solar heat is delivered to a heat-driven chiller (absorption [5], adsorption [58], desiccant [59], etc.) converting such heat into cooling energy [5,56]. The majority of the literature studies and commercial systems are based on evacuated tubes solar thermal collectors and a single-effect absorption chiller [1,60]. In climates where the availability of solar beam radiation is extremely high, the combination of concentrating solar collectors and a double-effect absorption chiller may be profitable [57]. In this case, a higher solar collector outlet temperature is required to drive