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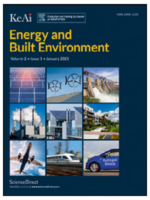

Photovoltaic-thermal solar-assisted heat pump systems for building applications: Integration and design methods

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ABSTRACT

The photovoltaic-thermal collector is one of the most interesting technology for solar energy conversion, combining electric and thermal energy production in a single device. Vapour-compression heat pump is already considered the most suitable clean technology for buildings thermal energy needs. The combination of these two technologies in an integrated ”photovoltaic-thermal solar-assisted heat pump” (PVT-SAHP) system allows reaching a high fraction of the building thermal needs covered by renewable energy sources and to improve the performances of both the photovoltaic-thermal collector and the heat pump. The first is cooled down increasing its energy conversion efficiency, while providing low-temperature thermal energy to the second, which benefits from a higher evaporation temperature.

The review study presents the state-of-art of photovoltaic-thermal solar-assisted heat pump systems intended to cover thermal energy needs in buildings, with a particular focus on the integration methodologies, the possible configurations, the use of different sources and the design of sub-system components. These issues are addressed by much scientific research, to improve the reliability and applicability of this technology, as an option for the building decarbonization. This study aims to present PVT-SAHP systems in an organic and critical way to propose a useful tool for future research developments. More in detail, the work highlights the fact that the integration of photovoltaic-thermal collectors as evaporator of the heat pump in direct-expansion systems allows the highest heat recovery and performances. However, the distinction of the two circuits lead to more reliable, flexible and robust systems, especially when combined with a second heat source, being able to cover both heating and cooling needs. The implementation of real-time control strategy, as well as the continuous development of the compressor and refrigerant industries is positively influencing this technology, which is receiving more and more attention from scientific research as a suitable solution for nearly zero energy buildings.

1. Introduction

Building heating, cooling and domestic hot water preparation play a key role in the transition from fossil fuels to more sustainable energy sources, since around 30% of final energy consumption is attributable to the building sector [1]. In the European Union, the fraction rises to 40% of final energy consumption and 36% of CO_2 emissions [2]. For this reason, the Directives introduced by the EU set ambitious goals for member states, requiring the entire energy chain, from production to consumption, to be more efficient, and buildings are not exempted from this change [3]. In particular, the Energy Performance of Buildings Directive (EPBD) [4], recast in 2010 [5] required all new public buildings to be ”nearly zero-energy” by the end of 2020 (public buildings since 2018).

In such a context, as suggested by the EPBD, the Building-integration of renewable energy sources (RES), in particular solar technologies, is fundamental for the decarbonisation of the buildings sector, especially in densely populated urban areas with limited space availability. As a confirmation, solar thermal is one of the most diffused renewable heating technology with 479 GW_{th}, cumulated capacity in operation by the end of 2019 (684 million square metres) having expanded almost 8-fold since the year 2000 [6]. Solar photovoltaic (PV) reached a comparable

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Abbreviations: DHW, Domestic Hot Water; DX-PVT-SAHP, Direct-Expansion Photovoltaic-Thermal Solar-Assisted Heat Pump; DX-SAHP, Direct-Expansion Solar-Assisted Heat Pump; HP, Heat Pump; HVAC, Heating, Ventilation and Air Conditioning; HX, Heat Exchanger; IDX-PVT-SAHP, Indirect-Expansion Photovoltaic-Thermal Solar-Assisted Heat Pump; IDX-SAHP, Indirect-Expansion Solar-Assisted Heat Pump; nZEB, nearly Zero Energy Building; PV, Photovoltaic; PVT, Photovoltaic-Thermal; PVT-SAHP, Photovoltaic-Thermal Solar-Assisted Heat Pump; RES, Renewable Energy Source; SAHP, Solar-Assisted Heat Pump; SC, Space Cooling; SH, Space Heating; WTS, Water Thermal Storage.

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installed capacity in operation by the end of 2020 (760.4 GW_{el}), undergoing a fast growth over the last decade, with a newly installed and commissioned capacity in 2020 equal to 139.4 GW, higher than other renewable power technologies [7].

Beyond the adoption of renewable energy sources, another important step of building decarbonization is the diffusion of clean technologies for Heating, Ventilation and Air Conditioning (HVAC). In this sense, heat pumps (HP) are considered the most promising technology for providing space heating (SH), space cooling (SC) and domestic hot water (DHW) from renewable energy sources in residential buildings [8], playing the main role in the future decarbonisation [9]. All over Europe, the market of newly installed HP increased in the double digits for 5 consecutive years and is expected to double within 2024 [10], while worldwide the sales growth has been around 5% during the last years and are expected to reach 22% by 2030 [11]. The reasons for such widespread diffusion are different: HPs can exploit low-temperature energy sources as ambient air, ground and geothermal wells and provide heat at a higher temperature. On the contrary solar thermal collectors are weather-dependent and not able to satisfy the whole heating demand in cold contexts [12]. Biomass still represents the most diffused renewable heat source [13], however the complexity of supply-chain management [14] and local pollutant emissions may limit its suitability for densely populated areas [15]. Heat pump systems, when operated inversely, can also cover cooling needs which acquired increasing importance due to global warming [16]. Moreover, HPs can be easily coupled to local RES, begin powered directly by the electricity produced, thereby reducing energy expenditure [17].

More in detail, in the last decades researchers paid great attention to solar-assisted heat pumps (SAHP), mainly vapour-compression HPs coupled with flat-plate solar thermal collectors [18]. Even though conventional thermal panels are generally adopted, the use of photovoltaic-thermal (PVT) solar collectors is expanding, due to their ability to produce both electric and thermal energy, which may be exploited by HPs, with benefits for both systems [19]. PVT renewable electricity may be self-consumed by the HP, which relies on the power grid when PVT electricity supply is not enough. The heat recovered by the hybrid collector can be exploited directly for domestic purposes or be transferred to the heat pump, which can then operate at a higher temperature, with consequent benefits in terms of overall system efficiency. Besides photovoltaic-thermal solar-assisted heat pump (PVT-SAHP) system represents a very competitive solution, it is also one of the most suitable to meet the nearly-Zero Energy Building (nZEB) standards both in heating-dominated climates [20,21,22] and in temperate regions, characterized by heating and cooling demand 23,[24].

Despite the promising role that PVT-SAHP may play in the decarbonisation of the building sector, no review study specifically addresses the combination of hybrid solar collectors and vapour-compression HPs. These systems are marginally investigated in the review studies on conventional SAHP, which mainly focus on the already well-documented combination of heat pumps with solar thermal collectors, often omitting hybrid PVT collectors. This article aims to offer a comprehensive and complete overview of PVT-SAHP systems, as an evolution of conventional SAHP, with a focus on the efficient integration of PVT and HP. Different configurations and technical solutions from the most relevant scientific literature are analysed and discussed. The state-of-art of the main sub-components is provided as well, thus offering critical analysis on the technological progress and stressing the attention on different design choices.

2. Solar-Assisted heat pump

Heat pumps can be mainly differentiated between mechanically-driven (also known as vapour-compression HP) and thermally-driven (also known as sorption HP), according to the form of energy used to run them. Even if great attention has been given to sorption HPs and their integration with solar collectors [25,26,27], vapour-compression HPs are more diffused for building thermal needs [28]. Studies have indeed shown that vapour-compression systems allow definitely better economic [29], energy [30] and CO_2 savings [28] results than sorption HPs, being also competitive with traditional heating systems, even without economic incentives [31]. Thus, for the scope of the article, only vapour-compression HP is considered, simply named HP.

Many factors affect HP performances, but the most important is the temperature difference between evaporation and condensation, thus the operative temperature of the low- and high-energy sources. Environmental heat sources, as outdoor air and ground, are often available at low temperatures affecting heat pump performance, thus making the exploitation of solar energy interesting in this sense. Several studies investigated the ways of combining HP systems and solar systems to ”assist” HPs through the exploitation of solar energy, in the form of electricity or thermal energy. Photovoltaic (PV) electricity may supply the compressor which is generally powered with alternating current, thus requiring a DC/AC inverter between the PV system and the machine. Some examples of HP powered with direct current were recently presented in the literature [32,33,34,35] leading to a new generation of PV-HP systems with benefits in terms of overall conversion efficiency. Even if some authors classifies PV-HP system as ”solar assisted” [36,37,38], the most literature identifies ”solar-assisted heat pump” systems as the combination of solar thermal technologies (e.g. conventional solar thermal and PVT) and HPs [18,39,40,41].

In SAHP systems solar energy is exploited as a heat source for the machine, alone or combined with other environmental sources, providing heat at a higher temperature concerning other sources. The higher evaporative temperature reduces electricity consumption and increases HP performances [42], as well as enhances heat extraction from solar collectors [43]. Moreover, the integration of HP and solar technologies allows overcoming many technical limitations of stand-alone solar thermal systems (e.g. the dependence on climate and solar availability [44], high heat losses, low efficiency and difficulties to reach high supply temperature in winter [40]). HPs are able to exploit the low-temperature energy from solar collectors, also in combination with a secondary heat source when radiation is low or absent, providing high-temperature energy for domestic applications, without any backup system.

The first SAHP concept was proposed by Sporn and Ambrose in 1955 [45] and later in the 70s the attention on this technology increased. Different opportunities for water heating for residential use and other low-temperature facilities started to be investigated [46]. The advantages of combining air-source HPs and solar systems, such as good performances in low-temperature operations and lower need for machine defrosting were evident [47,48]. Geothermal HPs may benefit as well from evaporative temperature increase and from ground regeneration through solar energy excess [49]. The influence of solar collector area, storage capacity and the optimal design of different components on energy performances were deeply analysed [50]. The introduction of variable-speed compressors allowed better matching between HP and solar gains under different weather conditions [51], while advancements of the refrigerants industries also benefited SAHP systems [52,53].

Different SAHP configurations are possible, according to the integration of solar collectors and HPs. Parallel and series configurations are the most known, being the first more robust and reliable for lower complexity in terms of hydraulic connections, design and optimization, even if the second option is more advanced and performing [40]. Dual-source systems when solar energy is combined with another heat source were soon recognised as promising [54] and have been further investigated for their large performances and energy savings with respect to simple parallel and series configurations [55].

3. Photovoltaic-thermal solar-assisted heat pumps

The hybrid photovoltaic-thermal technology represents an interesting solution for the co-generation of heating and electricity as it produces more renewable primary energy per square metre of installed

Table 1
List of existing review studies on heat pumps and solar technologies.

Authors	Year	The focus of the review
Chua et al. [72]	2010	Advancements in HP systems. Few examples of PVT-SAHP.
Amin and Hawlader [73]	2013	DX-SAHPs. No reference to PVT-SAHP.
Omojaro and Breitkopf [74]	2013	DX-SAHPs. Few examples of PVT-SAHP.
Kamel et al. [39]	2015	Solar systems (ST, PV and PVT) and their integration with HPs.
Buker and Riffat [18]	2016	SAHPs for water heating.
Yang and Athienitis [75]	2016	Building-integrated photovoltaic-thermal systems.
Sommerfeldt and Madani [76]	2016	PVT coupled with ground-source HPs.
Wang et al. [40]	2017	SAHPs for water heating. Some examples of PVT coupled with ground-source HPs are presented.
Poppi et al. [36]	2018	Techno-economic review of SAHP for residential heating.
Mohanraj et al. [77]	2018	Advancements of SAHP. Few examples of PVT-SAHP.
Nouri et al. [37]	2019	Focus on ground-source SAHP. Some examples of PVT-SAHP.
Wang et al. [38]	2019	Focus on air-source SAHP with ST, PV and PVT.
Shi et al. [78]	2019	Advancements in DX-SAHP with very few examples of PVT.
Lazzarin [79]	2020	Solar technologies and heat pumps. Few examples of PVT-SAHP.

collectors than the separate production through conventional PV and solar thermal [56,57]. Unfortunately, the adoption of hybrid solar collectors faces the main constrain in the operating temperature, especially at high latitudes and in the winter season [58], therefore not being able to meet the entire heating demand. Vice versa, when PVTs are coupled with DHW storages, PV cell production is affected by the high operating temperature, especially in periods with large solar radiation, low water consumption or when employing covered PVT [59]. Coupling the PVT with HPs allows covering thermal needs exploiting solar energy and maintaining PV cells at low temperature [60]. HPs can exploit thermal energy produced by PVT to cover building energy demand [19], while PVT electricity powers the HP compressor [61], reducing primary energy consumption. In such a figure, the fraction of renewable energy produced and self-consumed in-situ increases [30], with benefits in terms of CO_2 emission reduction [20]. At the same time, the active cooling of PV cells allows enhancing performances of both PVT and HP, with respect to the separated systems [62], with savings on electricity net consumption, heat extraction from environment and roof area [63].

In addition to the advantages for the sub-systems, relevant enhancements of overall energy performance are achievable with PVT-SAHP systems with respect to conventional SAHP employing solar thermal collectors and simple air-source HPs, as demonstrated by many studies during the last decade [64,65]. Rossi et al. [66] compared the above-mentioned three solutions under different climatic conditions, obtaining higher PVT electric efficiency and better performances in terms of primary energy consumption with PVT-SAHP than conventional SAHP or simple air-source HP. Analogous results were obtained by other studies comparing the COP of air-source HP and dual-source (air and solar) PVT-SAHP system [67,68]. The combination of PVT with HPs allows also higher primary energy-saving with respect to the traditional boiler-based system than air-source HPs powered by PV modules [69]. Moreover, the adoption of PVT collectors instead of traditional solar thermal collectors is beneficial in terms of energy saving and performance improvement [70]. The heat recovered and delivered to HP is slightly lower, but a larger amount of renewable electricity, higher seasonal performance factor and overall energy performances can be obtained with respect to other SAHP systems, as confirmed by different studies [56,71].

Conventional SAHP is an already well-documented technology, many review studies are present in the literature on the research improvement on the integration of heat pumps and solar technologies. As summarized in Table 1, those studies focus on conventional SAHP systems made combining HPs and solar thermal collectors, with few or no references to hybrid solar collectors. None of those review articles specifically focuses on the integration of heat pumps and PVT collectors in a unique system, even if the potentiality of PVT-SAHP systems are huge and many research works have been addressed the design and integration of PVT collectors and vapour-compression HPs in the last years, as shown in Fig. 1.

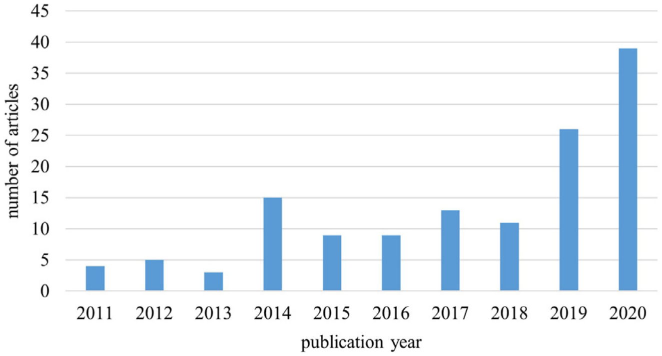


Fig. 1. Number of scientific articles on PVT-SAHP systems published in last the decade.

The current review article addresses PVT-SAHP systems for low water-temperature application which is the most diffused solution in building applications. Therefore, the attention is posed on HPs for water heating/cooling integrated with water-based flat plate PVT collectors, as they are the most efficient PVT technology and the most feasible for HVAC systems [80]. The classification is based on the way solar energy is exploited by the machine, being a crucial feature of PVT-SAHP, as it influences system performances and reliability. Indeed the following chapter is divided in direct-expansion (DX) systems, where the PVT collector is operated as the HP evaporator, and indirect-expansion (IDX) ones where a heat exchanger (HX) is interposed between PVT and HP. A further differentiation is made among single-source configurations, where solar energy is the only heat source for the HP, and dual-source systems, where another heat source is exploited in combination with solar energy. A conceptual scheme of different analysed options is reported in Fig. 2.

3.1. Performance indicators

The main performance indicators used in literature to describe PVT-SAHP systems and in particular the most important subsystems are described hereafter. PVT performances are generally evaluated based on electric and thermal output, thus electric efficiency (η_{el}), thermal efficiency (η_{th}) and the overall energy efficiency, also named first-law efficiency (η_I) calculated as the sum of the electric and thermal energy output. The electric efficiency of a PV module consists of the fraction of incident solar radiation that is converted in electricity, according to the following expression:

$$\eta_{el} = \frac{P_{el}}{G_t\, A_c} \tag{1}$$

where η_{el} is the electric efficiency of the module; P_{el} is the electric power generated by the module $[W]$; G_t is the total solar irradiance hitting the

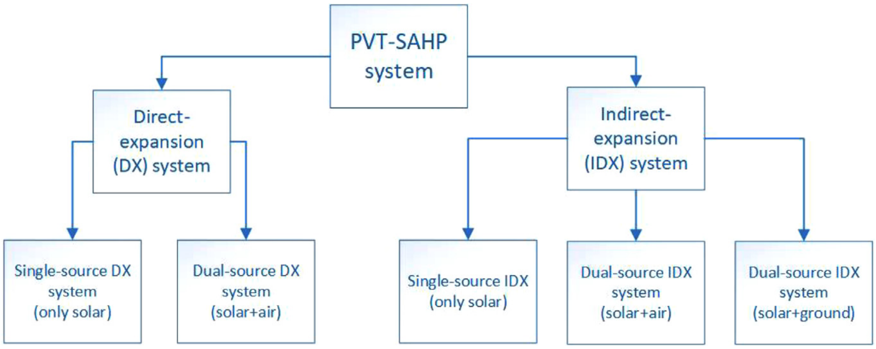


Fig. 2. Conceptual scheme of PVT-SAHP system configurations.

module $[W/m^2]$; A_c is the collector area, the front surface exposed to the Sun $[m^2]$.

The thermal efficiency of PVT collectors is calculated analogously to the conventional thermal collector:

$$\eta_{th} = \frac{\dot{Q}_{th}}{G_t\, A_c} = \frac{\rho\, \dot{V}\, c\, (T_{out} - T_{in})}{G_t\, A_c} \tag{2}$$

Where $\dot{Q}_{th}$ is the fraction of solar irradiance recovered by the heat transfer fluid and is expressed as the difference between thermal power of the heat transfer fluid at the outlet and inlet of the collector, ρ is the heat transfer fluid density, $\dot{V}$ is the volumetric flow rate, c is the heat transfer fluid specific heat, T_{in} and T_{out} are the inlet and outlet heat transfer fluid temperatures.

The heat pump performance is generally evaluated through the coefficient of performance (COP), which is defined as the ratio of the heat flow rate produced by the heat pump $\dot{Q}_{hp}$ to the electric power absorbed P_{el}:

$$COP = \frac{\dot{Q}_{hp}}{P_{el}} \tag{3}$$

Analogously, the performance of chillers and heat pumps operating inversely, is generally measured through the energy efficiency ratio (EER), which is defined as the ratio of the heat flow rate extracted by the chiller $\dot{Q}_{ch}$ to the electric power absorbed P_{el}:

$$EER = \frac{\dot{Q}_{ch}}{P_{el}} \tag{4}$$

Daily, monthly and seasonal performance of PVT and heat pump can be computed by integrating the above-mentioned Eqs. 1, 2, 3 and 4 over the considered period.

3.2. Direct-expansion systems

Heat pump systems with direct-expansion is the first kind of SAHP configuration, developed and investigated by many authors in years as a combination of conventional solar thermal collectors and heat pumps [81,82]. Direct-expansion solar assisted heat pump (DX-SAHP) is the simplest configuration, mainly dedicated to DHW production [83]. In direct-expansion photovoltaic-thermal solar-assisted heat pump (DX-PVT-SAHP) systems one or more PVT collectors are operated as HP evaporator making solar energy available to the machine. The HP refrigerant flows inside the heat absorber of the PVT collector-evaporator extracting heat during the phase-change process.

Research studies on DX-PVT-SAHP system, both single- and dual-source are described below, while details about each research study are summarized in Table 2. Only the most relevant works are described and discussed.

3.2.1. Single-source DX-PVT-SAHP

Single-source DX-PVT-SAHP for water heating is the simplest and firstly investigated application of hybrid PVT with HPs. In this configuration the hybrid collector is the only source of energy for the machine, as outlined in Fig. 3. The system may produce hot water at different temperature levels, according to the design, for space heating or DHW purpose, while cooling is generally not provided in such configuration.

Ito et al. [84] were among the first to present a DX-PVT-SAHP system for water heating, based on an optimized hybrid collector, following a previous research study [85]. Larger hydraulic connections allowed lower pressure losses and better refrigerant distribution along the PVT leading to a COP increase of around 5–10%, according to experimental results. Ji et al. [63] presented a single-source DX-PVT-SAHP system for water heating, modelled and simulated to evaluate the temperature distribution along with the evaporator. The model was further adopted to simulated performances under different climatic conditions as Tibet [86] and Hong Kong [87] with a proper improvement of the PVT collector, leading to promising system performances. Zhang et al. [88] introduced a new generation photovoltaic/loop-heat-pipe to assist the HP system for domestic hot water production. The prototype can work under two independent modes according to climatic conditions and temperature needs: the conventional DX-PVT-SAHP mode as well as the loop heat pipe photovoltaic-thermal mode, with direct solar water heating when radiation is abundant. Average COP under DX-PVT-SAHP was promising, while the thermal and photovoltaic average efficiencies resulted higher than in the loop heat-pipe PVT mode, demonstrating benefits from coupling with HP. Zhou et al. [89] employed PV/micro-channel hybrid collector as an evaporator in DX-PVT-SAHP systems for hot water production with good performances of both PVT and HP, reaching an average system COP equal to 4.7 in a 1-week experimental test in northern China. Further analysis with a proper numerical model [90] lead to system optimization in terms of PVT efficiency (14.5% electric efficiency and 59.7% thermal efficiency) and COP up to 5.2 [91]. Liang et al. [92] integrated an opaque ventilated micro-channel PVT façade system, able to reduce heat flux from the building, with a direct-expansion system for hot water production with good performance under real testing conditions.

The real-time compressor frequency control is fundamental in DX-PVT-SAHP systems. Li et al [93] developed a real-time integrated control method to adjust compressor operating frequency according to real-time radiation. The proposed control strategy showed relevant improvements in terms of PV electricity production and system COP, with respect to employing a common demand-driven control strategy. James et al. [94] as well, focused on reducing the electricity exchange with the grid, obtaining also good results in terms of energy efficiency, employing a feedback-controlled variable frequency drive (VFD) compressor which can work according to the available load.

Different numerical studies investigated the active cooling benefits on electric performances of PVT collectors operated as an evaporator in DX-PVT-SAHP systems [61], even in different climatic conditions [95,96].

Single-source DX-PVT-SAHP is generally adopted for hot water production, but few examples of PVT collectors operated as a condenser during night-time are present in literature. Kuang and Wang [81] tested a system in which the PVT-evaporator operates as condenser during the

Table 2
Studies on direct-expansion PVT-SAHP systems.

Author	Year	Study	Useful effect	Performances	Data type	Heat source
Ito et al. [84]	2005	num. and exp.	DHW, SH	COP: 1.8-4.4	1-day experiment	only solar
Ji et al. [100]	2008	experimental	DHW, SH/SC	max COP: 10.4, average: 5.4	4-day experiment	solar & air
Ji et al. [63]	2008	num. and exp.	water heating	COP: 3.8-8.4, average: 6.4	1-day experiment	only solar
Xu et al. [106]	2009	numerical	water heating	average COP: 4.8	1-year simulation	only solar
Fang et al. [101]	2010	experimental	DHW, SH/SC	COP: 2.75-2.85	2-hour experiment	solar & air
Fu et al. [103]	2012	experimental	DHW	average COP: 3.32-4.01	1-day experiment	solar & air
Tsai [107]	2014	num. and exp.	DHW	COP: 7.017.1, average: 7.09	experimental	solar only
Zhou et al. [89]	2016	experimental	water heating	COP: 3.1–5.6, average: 4.7	7-days experiment	only solar
Zhang et al. [88]	2017	experimental	water heating	COP: 3.03–4.37, average: 3.66	1-day experiment	only solar
Cai et al. [70]	2017	numerical	water heating	COP: 2.66 with 300 W/m^2	parametric analysis	solar & air
Ammar et al. [96]	2018	num. and exp.	water heating	COP: 4.84-7.03, average: 5.94	1-day experiment	solar only
Li and Sun [104]	2018	numerical	water heating	average COP: 3.10	monthly simulation	solar & air
Liang et al. [92]	2018	experimental	hot water	max COP: 3.1	7-days experiment	solar only
Li et al. [93]	2019	num. and exp.	water heating	COP: 4.4–5.2	2-days experiment	solar only
Lu et al. [108]	2019	experimental	water heating	average COP: 3.27	1-day experiment	solar only
Zhou et al. [97]	2019	num. and exp.	SH/SC	average COP: 6.16, average EER: 2.8	8-days experiment	solar only
Liang et al. [98]	2020	experimental	SH/SC	EER: 1.9-3.5	experiment	solar only
Lu et al. [99]	2020	experimental	SH/SC	average EER: 1.86-2.09	8-days experiment	solar only
Yao et al. [98]	2020	numerical	hot water	max COP 7.4	parametric analysis	solar & ground
James et al. [94]	2021	experimental	hot water	average COP: 6.4	1-day experiment	solar only
Yao et al. [109]	2021	numerical	DHW and SH	COP: 1.78-3.69	parametric analysis	solar & air

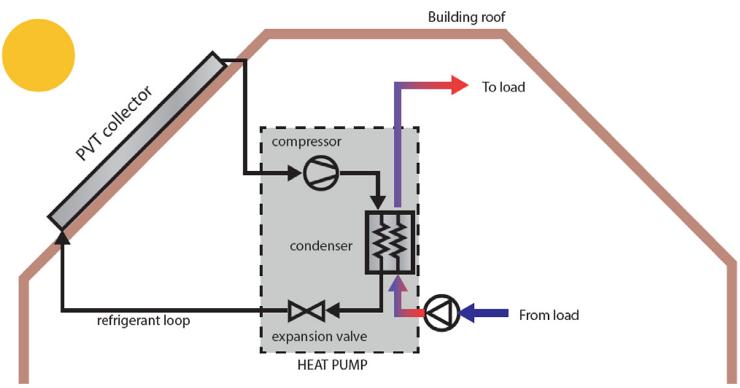


Fig. 3. Scheme of single-source DX-PVT-SAHP.

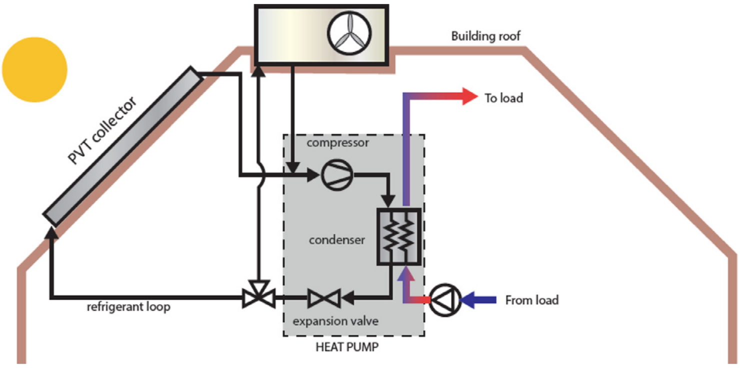


Fig. 4. Scheme of dual-source DX-PVT-SAHP.

night and stores cold water for daily needs. Analogously, Zhou et al. [97] experimented a DX-PVT-SAHP able to cool down the cold storage during night-time, till ice formation. Authors obtained refrigeration performance, with average daily EER between 1.86 and 2.84 during different experimental tests [98,99], despite this configuration required high condensation temperature (up to 80°C) and larger cold storage capacity (600 litres) than hot storage capacity (150 litres) to satisfy all the cooling need during day-time.

3.2.2. Dual-source DX-PVT-SAHP

DX-PVT-SAHP systems may rely on a second heat source through the adoption of a second evaporator operated in parallel with PVT collectors, as shown in Fig. 4. The presence of an additional heat source, generally air, improves system performances under adverse operating conditions, when the solar energy recovery is not enough to operate the machine [70]. The PVT refrigerant branch is generally connected in parallel to an air-source HX. The evaporation capacity of each HX, thus the fraction of refrigerant which flues in one or other branch of the circuit, depends on evaporators' temperatures, ambient temperature and heat gain. When solar energy is abundant, a higher fraction of refrigerant evaporates on the PVT side, vice-versa a higher environmental temperature (air or ground source) increases the evaporation capacity of the second source at the expense of PVT [70]. The solar circuit may also be bypassed when the machine is operated inversely, condensing in the air-source HX for water cooling on the user side, as experimented by some authors.

Ji et al. [100] proposed the evolution of the single-source DX-PVT-SAHP previously described. An air evaporator works in parallel to PVTs to boost the system when radiation is weak, being able to cover all building thermal needs, thus SC in addition to SH and DHW. Fang [101] investigated experimentally a DX-PVT-SAHP able to provide SH, SC and DHW in different operating modes according to load and boundary conditions. The machine is able to provide DHW and SH extracting energy from PVT collectors or the environment, while SC is provided discharging energy in the DHW storage or the environment. Further analyses of system performances under different operating conditions were studied through a proper mathematical model [102]. Fu et al. [103] adopted an innovative photovoltaic heat-pipe collector working in parallel to an air-cooled HX, to take advantage of the best heat source, according to weather conditions. In addition, DHW production can be covered by PVT/heat-pipes only, when solar radiation is abundant. An analogous system was experimentally tested by Li and Sun [104], consisting of a loop heat-pipe (LHP) PVT combined with an air-source HP for water heating, optimized through parametric TRNSYS simulations [105]. The parallel operations of the two systems allow providing hot water in different solar radiation conditions: high, medium or low.

The direct integration of borehole HX with DX-PVT-SAHP is generally not performed, even if there are examples of borehole HX employed in series to a DX-PVT-SAHP as proposed by Yao et al. [65] who used borehole HX on the user side, for water pre-heating before entering the machine. The system that may operate in single- or dual-source, was modelled and analysed with parametric simulations that showed interesting results in terms of performances.

3.3. Indirect-expansion systems

In the indirect-expansion photovoltaic-thermal solar-assisted heat pump (IDX-PVT-SAHP) configuration the hybrid collector does not coincide with the HP evaporator. Indeed, the refrigerant fluid is not expanded in the PVT collector, but an intermediate HX is placed between the solar circuit and the refrigerant circuit. HP and PVT collectors are basically separated, allowing for a more flexible system operation [110]. A water storage system may be adopted between solar circuit and HP circuit to reduce the dependence on solar energy instantaneous availability, or alternatively, the storage can be placed after the HPs, on the user side, as explained in the next section. PVT collectors may be integrated with HP systems as unique or additional heat source for the machine and their mutual position, the HX and the presence of additional thermal storages are the key features of indirect-expansion systems.

Research studies on IDX-PVT-SAHP solutions, both single- and dual-source are described below, while details about each research study are summarized in Table 3. Only the most relevant works are described and discussed in the following sections.

3.3.1. Single-source indirect-expansion PVT-SAHP systems

Single-source IDX-PVT-SAHP is the direct evolution of DX-PVT-SAHP and is also known as series- [18] or serial- [40] IDX-SAHP in some literature. PVT collectors heat a liquid stream of pure water or a mixture of water and anti-freeze liquid which transfer the heat to the machine through a water-to-gas evaporator, as shown in Fig. 5. Performance losses related to the instability of weather conditions are mitigated by the presence of the intermediate HX between solar collectors and the HP. The use of a HX between the machine and the solar collectors loop allows improving the system management and to choose a proper working fluid for the primary and secondary circuits, instead of filling PVTs with the HP refrigerant.

Different authors experimentally analysed single-source IDX-PVT-SAHP. Zhang et al. [111] developed a novel hybrid solar-assisted HP system, composed of a loop-heat-pipe hybrid collector which supplies the heat indirectly to the HP for hot water production. A proper virtual model allowed authors to design and size system components and to evaluate the effect of several operational parameters on energetic performances, which were subsequently evaluated experimentally. Moreover, the authors analysed the entire life-cycle to make an economic and environmental comparison with respect to conventional systems for different climatic contexts [112]. Dannemand et al. [113] studied the performances of a single-source IDX-PVT-SAHP for DHW production in 9 months of on-field monitoring and through further numerical simulations [114]. The system has double storage: cold buffer storage between PVT and machine, operating as HX and a DHW storage tank with a double serpentine, the upper is connected to the machine and the lower is directly heated by the PVT array. The collector is operated as a heat source for the machine during the winter season, while is able to directly produce DHW during the summer season. Different numerical studies of single-source IDX-PVT-SAHP investigated system design, optimal sizing and the effect of system parameters and environmental conditions on the performances [115]. TRNSYS is often adopted for preliminary design [116], performances evaluation under different operating conditions [117,118] and system optimization [119]. Different custom mathematical models are often employed for parametric techno-economic analysis [120,121,122].

3.3.2. Dual-source indirect-expansion PVT-SAHP systems

Dual-source indirect-expansion PVT-SAHP systems constitute a very interesting evolution of single-source IDX-PVT-SAHP. A second heat source, as the external air or the ground, is exploited in parallel or series with PVT. The machine is indeed equipped with two different evaporators and PVT collectors are often operated as an additional energy source of an air-source or a water-source HP. This configuration may provide heating, cooling and DHW, being suitable for a wide range of climatic conditions.

In the case of air-source HP coupled with PVT collectors, the two sources are generally connected in parallel with respect to the HP refrigerant circuit as outlined in Fig. 6. The second source allows operating the machine even with absent or low radiation, decreasing the dependence on sun availability, as experimented by Qu et al. [123] in their dual-source water heating PVT-SAHP system. Moreover, the presence of an additional independent heat source allows the HP to operate inversely, in cooling mode as proposed by Besagni et al. [19]. The authors carried a parametric study with a TRNSYS model to find out the optimal number of PVT, storage size and control strategy [68] and then developed an advanced dual-source IDX-PVT-SAHP system able to provide SH, SC and DHW through the combination of uncovered PVT collectors, air-source HX and a multifunctional reversible HP. The system is able to operate alternatively in water- or -air-source mode, according to the best environmental conditions, showing promising results in terms of COP when exploiting solar energy with significant improvement with respect to air-source functioning, as well as significant DHW load resulted directly covered by PVT collectors.

Another available option is to operate a water-source HP as a dual-source machine, connecting PVT collectors and air-source HX at the same water circuit as proposed by Aste et al. [23] who presented an energy and economic analysis of this solution. Energy simulations performed with TRNSYS software showed interesting results in terms of electricity production and self-consumption, COP increase and reduction of energy consumption for SH and DHW production with respect to uncoupled use of PVT and HP (up to 20%).

A further alternative to exploit water-source PVT and external air, is represented by the use of an integrated dual-source air/water evaporator (Fig. 7), also known as composite dual-heat-source evaporator [124] which is able to exploit two different heat sources. Wang et al. [124] were among the firsts to adopt a composite dual-source air/water evaporator in a PVT-SAHP system for water heating. The system is equipped with a novel dual-heat-source composite evaporator able to extract energy from both PVT water-glycol stream and air flow, obtaining better performances than conventional air-source HPs. According to the authors, particular attention is necessary on operating tempera-

Table 3
Studies on indirect-expansion PVT-SAHP.

Author	Year	Study	Useful effect	Performances	Data type	Heat source
Bakker et al. [57]	2005	numerical	DHW, SH	average COP: 2.59-2.71	10-years simulation	solar & geo
Bai et al. [116]	2012	numerical	water heating	average COP: 4.3	1-year simulation	only solar
Bertram et al. [128]	2012	num. and exp.	DHW, SH	seasonal performance factor (SPF): 4.5	2-years experiment	solar & geo
Zhang et al. [111]	2013	num. and exp.	water heating	COP(pvt*): 8.7	experimental	only solar
Varney and Vahdati [129]	2014	numerical	DHW, SH	-	1-year simulation	solar & geo
Wang et al. [124]	2015	experimental	water heating	COP: 2.74 to 5.98, average: 4.08	1-day experiment	solar & air
Putrayudha et al. [134]	2015	numerical	SH/SC	-	1-year simulation	solar & geo
Aste et al. [23]	2016	numerical	DHW, SH/SC	monthly average COP: 3–4.8	1-year simulation	solar & air
Qu et al. [123]	2016	experimental	water heating	COP: 2.63-5.05	1-day simulation	solar & air
Chen et al. [115]	2017	num. and exp.	water heating	COP: 2.68-2.91, average: 2.77		only solar
Besagni et al. [19]	2019	experimental	DHW, SH/SC	monthly average COP 2.97-3.08, monthly ave EER 2.99-3.45	1-year experiment	solar & air
Simonetti et al. [126]	2019	num. and exp.	water heating	nominal COP: 3.2 - simulated COP: 2.3–5.1	parametric simulations	solar & air
Del Amo [117]	2019	numerical	water heating	annual average COP: 3.56	1-year simulation	only solar
Sakellariou and Axaopoulos [135]	2019	numerical	DHW, SH			solar & geo
Sommerfeldt and Madani [21]	2019	numerical	DHW, SH	SCOP: 5.30	1-year simulation	solar & geo
Dannemand et al. [113]	2019	experimental	DHW	COP: 2.3 to 3.4	9-months monitoring	only solar
Naranjo-Mendoza et al. [141]	2019	experimental	DHW, SH		19-months monitoring	solar & geo
Braun et al. [118]	2020	numerical	SH	annual average COP: 3.6-4.8	1-year simulation	only solar
Cui et al. [120]	2020	numerical	SH	monthly average COP: 3.13-4.15	1-year simulation	only solar
Kong et al. [121]	2020	numerical	SH/SC	annual average COP: 4.5	1-year simulation	only solar
Obalanlege et al [122]	2020	numerical	SH	COP: 4.2 to 4.6	parametric	only solar

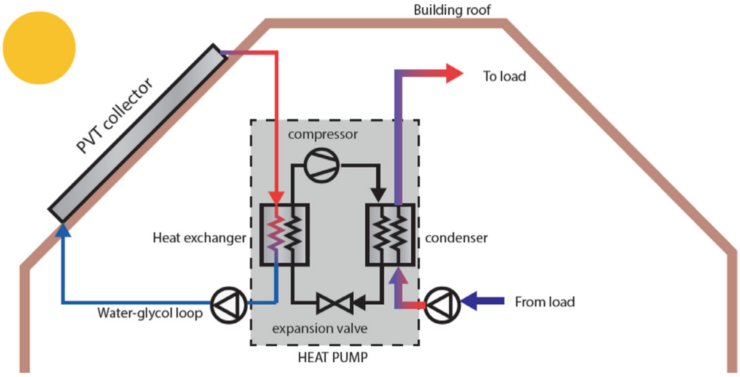


Fig. 5. Scheme of single-source IDX-PVT-SAHP.

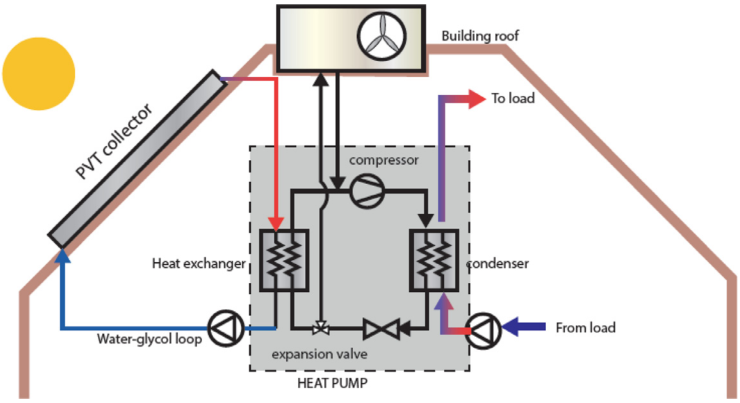


Fig. 6. Scheme of dual-source IDX-PVT-SAHP: separated PVT and external air HX.

ture management, since a higher water flow temperature may deplete performances due to the heat absorbed by the air flow. Long et al. [125] investigated the effect of air and water flow temperatures on system performances, quantifying the performance gain of an integrated dual-source HP with respect to a conventional air-source HP. Simonetti et al. [126] experimentally tested a novel IDX-PVT-SAHP fabricated with an integrated dual-source evaporator, obtaining up to 14% of performance increase with respect to conventional air-source HP. The authors also conducted a numerical study on the optimal design of refrigerant, fluid and air flows inside the evaporator through MATLAB software.

Hybrid PVT collectors may also be coupled with ground-source HX in water-source HP systems. The combination of solar thermal technologies and ground-source HPs is a very interesting solution, especially in northern countries where ground-source systems are more cost-effective than employing air-based technologies which don’t provide satisfying performances with cold temperatures [127]. Hybrid collectors may be coupled with ground-source HPs leading to a double benefit: improvement of photovoltaic efficiency due to the cooling of PV cells and increase of machine COP thanks to higher evaporative temperature [128,129]. A further advantage is the regeneration of borehole HXs in the location

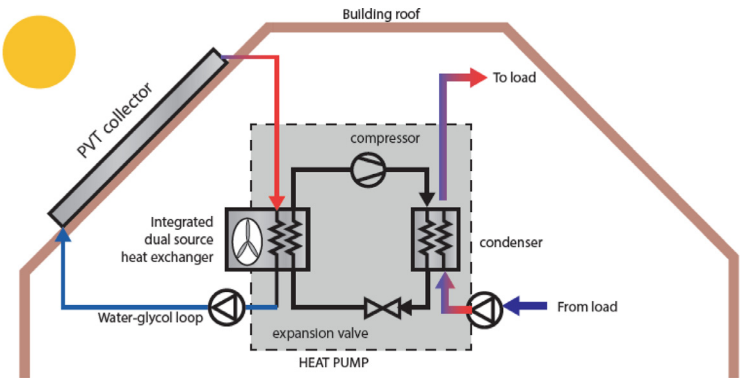


Fig. 7. Scheme of dual-source IDX-PVT-SAHP: integrated air/water evaporator.

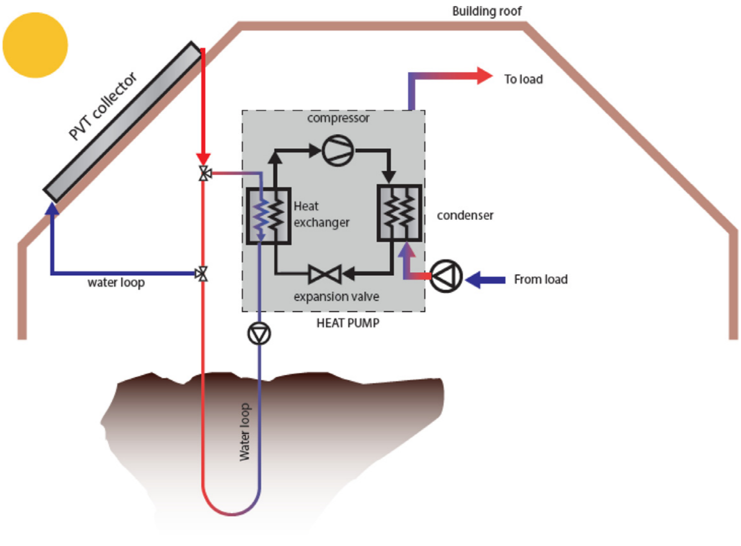


Fig. 8. Scheme of dual-source IDX-PVT-SAHP: PVT and geothermal HX on same water circuit.

where a high density of ground HXs causes large and continuous heat extraction from the ground, reducing average ground temperature, thus affecting HP performances. The combination of solar collectors with HPs may reduce the heat extraction during sunny days, while an extra amount of solar heat can be re-injected in the ground during summer, reducing the heat source degradation [130]. The presence of solar thermal technologies, such as PVT collectors, may increase the number of ground-source HPs in a neighbourhood, enhancing renewable energy exploitation in heating-dominated regions [131,21].

The first studies on PVT and ground-source HPs date back to the 80s, when first analyses on different configurations of ground HX and SAHP were presented [132]. Successively, much other research has been carried on ground-source SAHPs and in particular with hybrid collectors. The PVT system can be connected to a geothermal circuit on the evaporator side of a conventional water-source HP, as shown in Fig. 8. In some cases the solar circuit needs to be filled with anti-freeze mixtures, requiring for an intermediate HX to separate solar and geothermal circuits, as firstly proposed by Bakker et al. [57] (Fig. 9) or alternatively with a water thermal storage [133]. Both series [128,129,21] and parallel 134,135] configurations has been deeply investigated. According to results of the IEA Solar Heating and Cooling and Heat Pump Program research (T44A38), glazed PVT collector operated in parallel to ground-source HP system is the best configuration from a seasonal performance factor (SPF) point of view, while the series configuration is preferable when shorter borehole HX and regeneration are needed [8].

Several authors relied on numerical tools to investigate the coupling of PVTs and geothermal HP. TRNSYS software is largely used in this sense to estimate HP performance benefit due to PVT presence [128,129], even in different weather conditions [136,133], as well as to define the optimal system configuration [137,135,127]. Regarding the modelling strategy of such systems, the traditional thermo-electricity analogy method was effectively used for analyzing heat transfer processes in PVT-SAHP systems. However, this methods method showed some limits in analysing complex thermal systems quantitatively [138]. Recently, Wang et al. [139] demonstrated that the heat current method is an optimal solution for the modelling of double-evaporators PVT-ground-source HP (PVT-GSHP). A model-based performance control strategy was implemented by Xia et al.[140] integrating an adaptive model and a genetic algorithm to define real-time control settings for PVT-GSHP. The proposed advanced control strategy was be able to enhance PVT-GSHP performances with respect to traditional ones.

4. PVT-SAHP Component design

The performances of PVT-SAHP systems are strongly related to the development of each sub-component, to their correct integration and arrangement. In the following sections, the state-of-art of the main PVT-SAHP sub-components is provided, stressing the attention on common design choices and the most advanced solutions presented in recent studies. It must certainly be underlined that proper design of each component and its systemic integrations in the whole PVT-SAHP system must be carried out according to the specific features of each application case (e.g. climatic conditions, buildings thermal loads, etc.).

4.1. PVT Collector

The idea of combining photovoltaic and solar thermal production in a hybrid collector goes back to the 70s. Wolf [142], Kern and Russell [143] and Hendrie [144] were among the first that analysed the

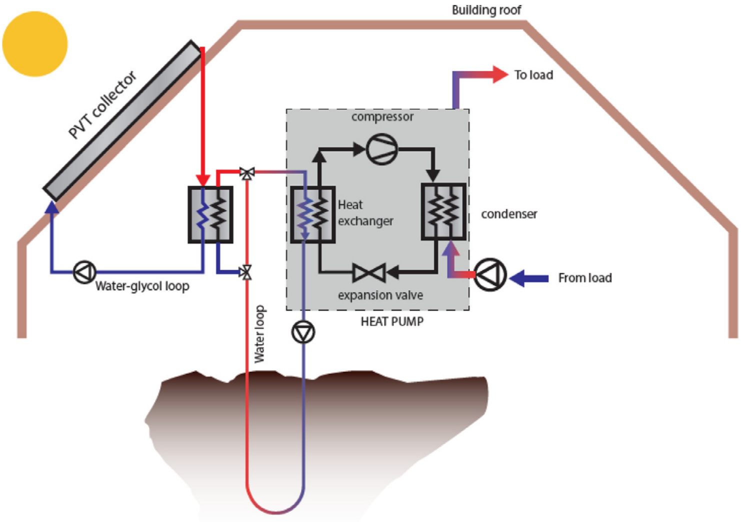


Fig. 9. Scheme of dual-source IDX-PVT-SAHP: PVT and geothermal HX with intermediate HX.

potentiality of coupling photovoltaic and solar thermal technologies in a single device. The adoption of a heat recovery system on the back of the PV panel leads to the so-called photovoltaic-thermal (PVT) solar collector. This system has two main advantages. Firstly, the heat recovery allows the enhancement of conversion efficiency, in particular for crystalline silicon (c-Si) cells, while the thermal energy, otherwise wasted, can be used for different low-temperature applications as domestic hot water (DHW) production and space heating. Secondly, the integration of photovoltaic and thermal systems into a single unit, allows the reduction of the total collector area, increasing the exploitation of the solar source [145]. Various studies [146,147,56] concluded that a well-design hybrid PVT system can achieve better performances compared to the separated production of thermal and electric energy [148]. This is a fundamental theme from the viewpoint of nZEB design, since the lack of surface availability is one of the main bottlenecks for local clean energy production. For these reasons, the largest area of interest for hybrid PVT systems is the residential one, where electricity and thermal energy production with compact devices is crucial, making PVT suitable for small roof surfaces [149].

Water-based PVT is the most investigated technology in combination with HP systems, as can achieve better performances than air-based systems [150,151] and be easier integrated into PVT-SAHP systems [152]. Among the different kinds of solar modules, flat-plate collector are the most feasible for low-temperature applications, easier to be manufactured and to be building-integrated than other technologies [153]. Only few examples of vacuum-tubes [154] and concentrating collectors [155,156,157] integrated with HPs are present in the literature.

The presence or not of an external glass cover forming an air gap over the PV cells is a distinctive feature of solar collectors, which can indeed be divided in ”uncovered” and ”covered” PVT. The presence of glass cover allows reducing thermal losses towards the environment and is widely employed in conventional solar thermal, where the enhancement of thermal yield is very important. Uncovered PVT are indeed more influenced by external ambient conditions (e.g. air temperature, wind speed, etc.) not being able to achieve high water temperatures when operating in cold weather conditions [158]. Nevertheless, the presence of the external cover increases optical losses affecting electric efficiency [159], which is very important in PVT collectors. In general, the use of covered PVT allows operating the HP at higher evaporation temperature, since the presence of the glass cover increases water temperature and heat gain. Thus, the machine may benefit from coupling with PVT in terms of overall system COP, even if electric and exergy efficiency are lower than employing uncovered PVT [160]. Both solutions are adopted as reported in Table 4, even if uncovered PVT are mostly employed for their simpler and cheaper manufacturing process, as well as their larger electric production.

A fundamental PVT component in the SAHP system is the thermal absorber, usually made of metal, rarely of polymeric material. Several thermal absorbers typologies have been developed by the solar thermal industry through the years to reduce thermal resistance between the top surface and working fluid, as well as manufacturing complexity and cost. Many kinds of absorber arrangements were adapted in hybrid collector design, even if the presence of PV cells requires further considerations on temperature distribution [149]. Traditional thermal absorbers are made by metal tubes with different arrangements, attached to the metal plate in the so-called sheet-and-tube or fin-and-tube absorbers [161]. The simple manufacturing method and the good heat transfer properties made this kind of absorber very diffused in the PVT industry [80]. Both circular [61,101,123,93,70,115,96,94] and rectangular [106] shape channel are diffused in PVT-SAHP systems, with different arrangements, as parallel [106,101,61,123,96] or serpentine 70,93,94]. Many authors chose to use copper tubes welded to aluminium absorber plates [57,101,61,70,96,93], others preferred full aluminium [106] or full copper [123] absorbers.

Heat-pipe absorbers are widely used in PVT collector for their high thermal efficiency [162], thus high heat available for the HP operations [103,111,88,115,104], as well as micro-channel heat pipe array (MHPA) absorber [89,92]. Those systems are particularly feasible in a cold region, being able to overcome some problems occurring in refrigerant-based systems: unbalanced refrigerant distribution, possible leakages, difficulty in retaining operating pressure conditions [163].

In the last decade, the roll-bond absorber resulted one of the most diffused technologies [164] for its consolidated fabrication process and very high energy performances with respect to other solutions [68]. Roll-bond absorbers are also extremely versatile with respect to traditional sheet-and-tube or innovative MCHP arrays, allowing for different channel shapes and distribution. Parallel [59,165], serpentine [19,97,108], honeycomb [109] and bionical (fractherm) [116] arrangements were adopted in PVT-SAHP systems. Several examples of roll-bond absorbers were presented, mainly in aluminium [116,67,165,109], but also steel HX [19] and polyethylene HX are adopted [120]. Section of most diffused thermal absorbers is reported in Fig. 10.

The integration of electric and thermal components, indeed PV laminate and thermal absorber is a crucial step of the PVT manufacturing process which affects the overall energy performances. The most diffused method consists of attaching an absorber plate to the back of a commercial PV module, employing gluing techniques [93,97,108,123,115,120] or mechanical fixing [59,89]. Both options,

Table 4
Most relevant PVT technologies adopted in PVT-SAHP systems and their energy performances.

Author	PVT technology	Electrical eff.	Thermal eff.	Data acquisition
Bakker [57]	uncovered, pc-Si cells laminated a copper sheet-and-tube absorber	-	-	-
Ito [84]	uncovered, pc-Si module attached on a roll-bond absorber	-	-	-
Ji [63]	uncovered, sc-Si cells laminated on a sheet-and-tube absorber	nom. 14.7% - exp. 13% to 14.1% (13.7% av.)	-	1-day experiment
Fang [101]	uncovered, PV module, attached to aluminium plate, copper tubes	10.4% (exp. av.)	-	2 hr experiment
Fu [103]	covered, PV cells laminated on an aluminium plate with heat-pipe absorber	10.7% to 11.7%	61.1% to 82.1%	1-day experiment
Bai [116]	sc-Si cells laminated on an aluminium roll-bond absorber	10.1% to 10.7% (annual av. 10.3%)	37% to 57% (annual av. 49.3%)	1-year simulation
Zhang [111]	covered PV/loop-heat-pipe with pc-Si PV cells	10% (daily av.)	40% (daily av.)	experimental
Tsai [107]	uncovered, pc-Si module, with multi-port copper tubes adhered on back	12.2% - 12.15% (ave 12.43%)	73.7% - 74% (ave 73.8%)	experimental
Zhou [89]	uncovered, PV module weld on a micro-channel-evaporator	15.4% (daily av.)	54.2% to 57.1% (annual av. 56.6%)	7-days experiment
Wang [124]	uncovered, PV module attached on a MHPA absorber	13.7% to 14.9%, (daily av. 14.5%)	31.7% to 51.5%	1-day experiment
Qu [123]	uncovered, sc-Si PV module attached on copper sheet-and-tube absorber	8% to 20%	-	1-day experiment
Zhang [88]	uncovered, PV/loop-heat-pipe	10.9% to 12.8% (daily av. 12.1%)	57.5% (daily av.)	1-day experiment
Chen [115]	covered, pc-Si panel attached to a heat pipe absorber	8.8% to 17%	17% to 61.3% (daily av. 35.4%)	1-day experiment
Cai [70]	covered, PV module attached to aluminium plate with copper tubes	15.36% with 300 W/m^2	44.16% with 300 W/m^2	parametric simulations
Liang [92]	uncovered, sc-Si PVT module with serpentine microchannels	9% (daily av.)	-	1-day experiment
Ammar [96]	uncovered, pc-Si PV module attached to aluminium plate with copper tubes	11.98% to 11.56%	88.68% to 76.64%	parametric simul.: 300–1000 W/m^2 radiation
Besagni [19]	uncovered, pc-Si PV module attached to a steel roll-bond absorber	daily av. 12% to 16.5%	daily av. up to 32%	1-year experiment
Lu [108]	uncovered, PV module attached with EVA sealant to a roll-bond absorber	daily ave. 7.51%	daily ave. 49.9% -	1-day experiment
Zhou [97]	uncovered, PV module attached with EVA sealant to a roll-bond absorber	ave. 8.7%	-	1-day experiment
James [94]	uncovered, commercial pc-Si PVT module	15% to 18%	up to 65%	1-day experiment

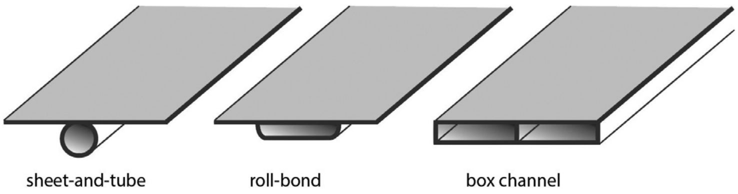


Fig. 10. Scheme of the most diffused absorber layouts.

however are characterized by low heat transfer coefficient due to air presence among the two layers. Moreover, in the gluing methods, generally employed through the use of thermo-conductive glues with high-temperature resistance, condensation may occur inside layers, leading to higher thermal resistance [146] and temperature misdistribution [166]. The mechanical bonding, instead, needs additional profiles, joints, screws and clips, leading to higher manufacturing cost and collector weight.

More advanced manufacturing solutions have been developed through years [167], as the direct lamination of the whole photovoltaic-thermal package in one step [168]. Direct lamination of PV cells on a rear back-sheet represents one of the leading techniques in the production of conventional PV modules. PV cells are generally laminated between a double layer of encapsulants, with a glass layer on top, while a TPT layer and metal rear plate are placed on the bottom [167]. This technique may be adopted for PVT manufacturing as well, simply substituting the rear support of the PV module with a metal absorber, indeed improving thermal performances with respect to simple bonding [169] and gluing methods [170]. Particular attention is necessary for electric insulation of the metal absorber, requiring multiple encapsulant layers between the PV cells and the metal absorber or for the insulating coating to be applied directly on the metal plate [161]. Differences among the most diffused integration techniques are reported in Fig. 11.

Direct lamination of PV cells may be applied with different absorber typologies as traditional sheet-and-tube collector [57,100,70,122], roll-bond absorber [171,116,97], heat-pipe absorbers [103,111]. The high pressure occurring in the lamination chamber may damage pipes and water conducts on the back of the absorber plate [161]. Postponing pipes welding after PV cells lamination may be a solution in sheet-and-tube absorbers [100]. Roll-bond absorber and box channel absorbers suffer less this problem, being more feasible solutions to manufacture high efficient PVT collector with direct lamination.

An advanced lamination technique allows fabricating a covered PVT collector with a single glass layer. The PV-absorber may be laminated without a top glass layer while an external glass cover is posed at a distance of few centimetres, creating an air gap for thermal insulating purposes. This manufacturing process is challenging due to the absence of the top glass layer in contact with PV cells and few examples are present in the literature [170,165]. Nevertheless, the absence of the double glass layers in covered PVT collectors allow to reduce optical losses

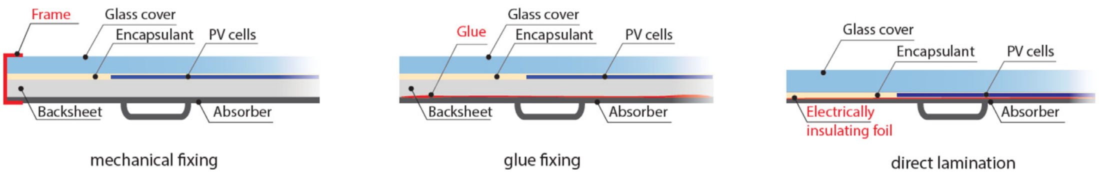


Fig. 11. Scheme of the most diffused integration techniques for PVT collectors.

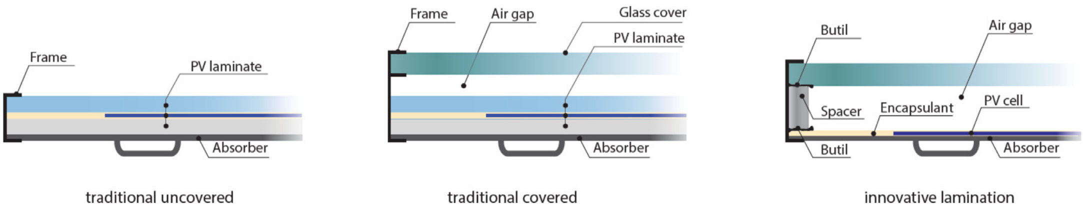


Fig. 12. Advanced PVT lamination compared with traditional covered and uncovered PVT layout.

and increase electric performances, being comparable to uncovered PVT collector [165]. Differences between innovative and conventional lamination are reported in Fig. 12.

4.2. Compressor

The compressor is a fundamental component of PVT-SAHP systems, because its choice may deeply influence system performances and reliability. Rotary-type compressors (scroll and rolling pistons) replaced reciprocating compressors as reference technology in domestic and small commercial applications, thanks to higher reliability and efficiency [172]. Scroll compressors in particular, are more suitable for small and medium air conditioning systems for higher capacity and lower vibrations, thus lower noise. Even if reciprocating and rolling pistons compressors are still considered the more suitable solutions for small applications [173]. Centrifugal compressors, more expensive but also more efficient, are justified only for large HP size, for multi-family flats, industrial and large commercial applications. Indeed no evidence is still present in SAHP literature, even if R&D in the small centrifugal compressor may lead to the replacement of scroll compressors for chilled-water systems in middle size application, as their higher energy efficiency may overcome the higher investment cost [174]. Among PVT-SAHP experimental system, the most diffused are rotary compressors [84,89,126,104], but also reciprocating [115], scroll [96] and rolling rotor [97].

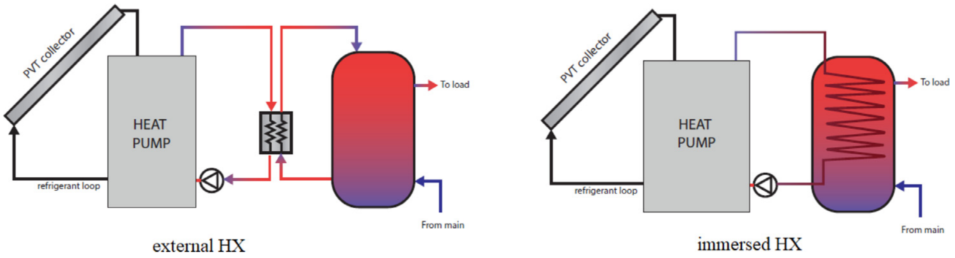
In SAHP, both variable and fixed speed compressors are diffused, even if modulating ones are preferred as they allow to optimize the refrigerant mass flow rate, so the evaporating temperature. This solution allows increasing HP performances [175,86] and constitutes the most diffused design choice in PVT-SAHP systems [100,89,84,106,103,61,93,126,97,94] even if some examples of fixed-speed compressors are present [115,96,104]. Especially in direct-expansion systems, variable frequency compressors allow maintaining a proper match between the machine and the PV-evaporator under different weather conditions [51], with important COP increase with respect to fixed-speed compressors [106,73]. Hence, a variable-speed compressor operating in solar-driven conditions, may increase the frequency and so refrigerant mass flow rate, under high solar radiation, while decreasing frequency, then refrigerant mass flow rate and heat output, under poor sun availability [86]. This is typical for single-source DX-PVT-SAHP systems, where the machine is operated according to solar availability and excess heat output is stored for a period of low solar radiation, as proposed by Li et al. [93]. The use of a vapour-injected compressor represents an interesting option for DX-PVT-SAHP operating in cold regions, with large temperature lift and scarce solar radiation, even if few experimental studies are available [108,109].

On the contrary, in load-driven conditions, a variable-speed compressor operating with high solar radiation may reduce its frequency, reducing refrigerant mass flow and power input, but increasing the evaporative temperature. It is a typical summertime condition, resulting in higher COP with the same heat output. Vice versa in wintertime, when solar radiation and ambient temperature decrease the increase of compressor speed allows achieving higher refrigerant mass flow rate and heat output, helping the system in covering heating loads, even though a lower evaporative temperature leads to lower COP [176]. This is typical of dual-source IDX-PVT-SAHP systems, where the evaporation is not directly dependent on solar conditions and a complementary heat source may be exploited when solar radiation is not available. The presence of a variable frequency compressor may also help to prevent the superheating of refrigerant or damaging flow rate and heat output, helping the system in covering heating loads, even though a lower evaporative temperature leads to lower COP. Proper control of compressor frequency, together with the expansion valve, allow to reach the suitable evaporative conditions [177].

4.3. Energy storage

The stochastic and intermittent nature of solar radiation is the main constraint to a wide diffusion of solar-based energy systems. A concrete solution to reduce the mismatch between solar radiation and heating load is storing the energy produced by photovoltaic (electricity) or by HPs (hot/cold water) [73,178]. The most diffused energy storage solution for solar thermal collectors and HP systems is water thermal storage (WTS). Water is cheap, non-toxic and it can directly fill storage tanks for DHW purposes or space heating/cooling. Horizontal and vertical tanks are available on the market, even if the first kind is less diffused in solar water heating applications for their more difficult and complex design [179] due to the faster stratification depletion with respect to cylindrical vertical storages and the consequent lower overall thermal performance [180]. The mixing of hot and cold water may be reduced using particular devices to maintain elevated thermal performances: multiple draw-off levels from the tank [181], obstacles at tank hot water inlet [182], baffle plates [183] have been investigated and reported to be advantageous. The velocity of inlet hot water is a key factor that influences thermal stratification and depends on flow rate and inlet cross-section. The higher the velocity, the higher the turbulence at the tank inlet, which undermines the stratification in the water storage [184].

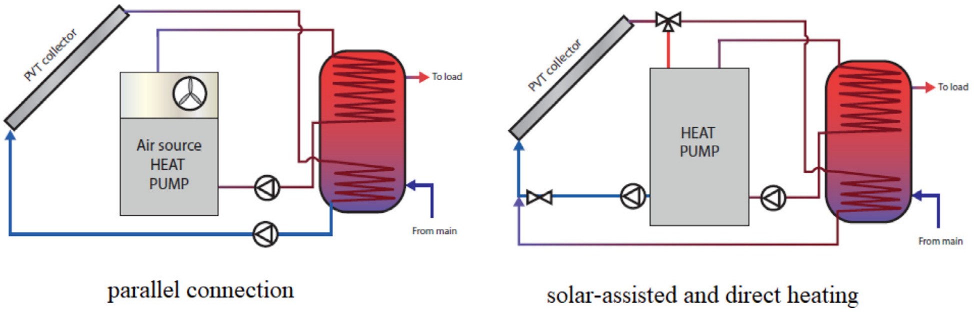
In water-heating system, a water thermal storage is generally placed on user side [100,61,124,93,108,122] and heated up by the heat pump according to the setpoint temperature, through external HX [92] or an immersed condenser coil in the water storage [89,88,104,94], as outlined in Fig. 13.



external HX

immersed HX

Fig. 13. Integration of water thermal storage in PVT-SAHP on the load side.



parallel connection

solar-assisted and direct heating

Fig. 14. Integration of water thermal storage in PVT-SAHP for direct heating through PVT.

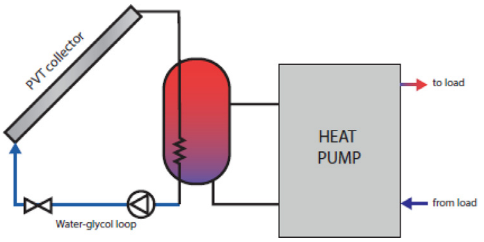


Fig. 15. Integration of water thermal storage on the solar circuit of the PVT-SAHP system.

PVT collector may be directly connected to the water storage for direct heating when solar energy is abundant, in different configurations, as reported in Figure 14. The heat pump may be bypassed by PVT collectors that discharge heat in the bottom side, in parallel to the machine which is generally connected to the upper side [57,23,113,19,122], or arranged to allow both direct PVT heating and solar-assisted mode.

Alternatively, an intermediate thermal storage can be interposed between PVT collector and HP (generally named ”solar storage”) in IDX-PVT-SAHP systems to be exploited as water-source for the machine [116,124,70,185,113,19,117], as reported in Figure 15. This high-temperature source can be exploited by the heat pump even in zero radiation hours, or during night-time, being suitable for de-frosting operation in dual-source systems [19]. The correct sizing of the water storage is fundamental to obtain good system performances and ensure load supply. Many researchers investigated how to optimize storage size during the design process. Kuang et al. [186] formulated the mathematical relation between system COP, collector efficiency and thermal storage volume, identifying an optimum ratio of the storage volume to the collector area. Kim et al. [187] analysed variation of hot water temperature for different storage sizes through a dynamic energy simulation. Small reservoirs showed larger transient performance degradation while larger reservoirs caused additional heat loss in hot water storage.

The interest in phase-change materials (PCM) for thermal applications in buildings has recently increased for the possibility to store a large amount of energy through the phase change process and realising it during the inverse process [188,189]. Indeed, the lower storage volume is necessary with respect to conventional WTS [190]. In particular, solar-assisted heating systems with PCM as thermal storage have received major attention and different solutions have been investigated [191,185]. Kaygusuz et al. [55] used commercial calcium chloride hexahydrate as thermal storage for an experimental SAHP for residential heating in Turkey. Series, parallel and dual-source configuration were analysed. The dual-source configuration had larger advantages from the presence of the PCM storage. Qui et al. [192] investigated the use of micro-encapsulated PCM slurries as working fluid of a hybrid solar collector connected in series to the HP for water heating. The study showed that the system may have better performances than conventional air-source HPs and solar-assisted HP systems, if system components are properly sized and parameters are optimized.

Seasonal storage or large volume storage can be used to store low-temperature heat, which is indeed not high enough to be directly used for domestic applications, thus a HP system is necessary to increase the temperature to a useful level. This solution is typically adopted in middle-large scale applications, as public buildings, offices and city districts and few examples of boreholes employed as seasonal storage are present in IDX-PVT-SAHP [141].

Some examples of electrochemical storages employed in PVT-SAHP systems are present [63,101,193,155,111,88,93], but very few details are provided about the technology chosen and no comparative analysis with thermal energy storages is available. Energy storage choices in PVT-SAHP systems are reported in Table 5.

4.4. Refrigerants

The choice of the refrigerant should consider several aspects and represents a major design choice in SAHP, especially in direct-expansion systems [194]. From the thermodynamic point of view, to achieve good system performances the refrigerant should have high thermal conductivity, phase-change enthalpy, heat transfer coefficient, critical temperature and low operating pressure, while low freezing point, viscosity and specific volume are instead necessary to reduce the dimensions of the machine, as well as its power consumption and costs. From a security and environmental point of view, the refrigerant is required to be non-toxic, non-polluting and inflammable, slowing down the diffusion of refrigerant machines in domestic context for lack of suitable refrigerants [195]. In this sense, the introduction of R12 opened the growth of refrigerant industries [196], finding application also in DX-SAHP with better performances than other refrigerants [53]. However,

Table 5
Different kinds of storages adopted in PVT-SAHP systems.

Author	Type	Technology	Size	Notes
Bakker et al. [57]	thermal	water	170 litres	storage for DHW with double serpentine (PVT and HP)
Ji et al. [63]	electric	AC storage	150Ah	on PVT side
Xu et al. [106]	thermal	water	150 litres	water heating, user side
Fang et al. [101]	electric	DC storage	-	on PVT side
Fu et al. [103]	electric	DC storage	-	on PVT side
	thermal	water	560 litres	water heating, user side
Bai et al. [116]	thermal	water	-	intermediate WTS on source side
Zhang et al. [111]	electric		12V/100Ah	
	thermal	water	100 litres	on user side
Tsai [107]	thermal	water	200 litres	on user side
Wang et al. [124]	thermal	water	64+80 litres	2 WTS, on both PVT and user side
Zhou et al. [89]	thermal	water	1000 litres	on user side, with immersed-condenser
	electric	DC storage	-	on PVT side
Batteries Qu et al. [123]	thermal	water	500+200 litres	2 WTS, on both PVT and user side
Zhang et al. [88]	electric		150 Ah	
	thermal	water	150 litres	on user side
Li et al. [104]	thermal	water	150 litres	on user side
Liang et al. [92]	thermal	water	150 litres	on user side
Li [93]	thermal	water	150 litres	on user side
	electric	-	500VA/12 V	
Besagni [19]	thermal	water	186+300 litres	2 WTS: DHW with double serpentine (PVT and HP) and intermediate WTS on source side
Lu et al[108].	thermal	water	620 litres	on user side
Del Amo et al. [117]	thermal	water	-	4 WTS: 2 intermediate WTS and 2 WTS on user side
Zhou et al. [97]	thermal	water	150+600 litres	a hot WTS and an water/ice storage
Dannemand et al. [113]	thermal	water	160+200 litres	2 WTS: DHW and intermediate storage
Yao et al. [65]	thermal	PCM	-	on user side
James et al. [94]	thermal	water	150 litres	on user side

R12 and other very diffused refrigerant in HP systems have been discovered to damage the environment and their use has been restricted and regulated. R22 was the principal substitute in residential applications due to its good thermo-physical and thermodynamic properties [197]. Performances of DX-SAHP with R22 have been widely investigated [186,53,198] and many applications in PVT-SAHP systems are present in literature [84,100,106,124,93,125,117,97,104].

The necessity to shift from traditional refrigerants to more environmental-friendly gas mixtures, with lower impact on ozone and greenhouse effect pushed the research on alternatives to R22, such as R407C [198,199] , R407A [200], R404A [109] and R410A [201,202,[97] that were identified as the leading replacements in air-conditioning and HP applications after the fading out of CFC mixtures [203]. The low critical pressure and temperature make R410A not feasible for high-temperature HPs, but many research found its performances comparable or larger than R22 [202] and it was reported to absorb and discharge heat more efficiently than R22 [201], that made this refrigerant very used in PVT-SAHP systems [116,97,126,19]. R134a is another very diffused refrigerant in PVT-SAHP applications [101,95,103,111,61,123,115,96,92]. This refrigerant is more suitable than R410A for high-temperature applications like non-renovated buildings [203], due to its higher critical temperature, allowing for water heating above 70°C, while HP systems employing R410A are limited to water supply temperature around 65°C [204] . On the contrary, R410A has a higher density than R134a, allowing for a more compact machine and lower costs, but also being more suitable for cold climates, since R410A allows better performances at low operating temperature. Few studies evaluated the application of modern low-GWP refrigerants in SAHPs, as R32 [94] R600a [88], R744 [205], R170/R290 mixtures [206] and CO_2 [207].

5. Discussion

According to the outcomes of this study, it is possible to confirm that there is no unique preference in the integration of PVT and HP systems, direct-expansion PVT-SAHP systems represent an interesting solution for water heating for their easier construction and lower complexity and cost, thanks to the absence of any intermediate HX between the HP and the PVT that is fully integrated as an evaporator. However, this characteristic makes direct-expansion configurations more vulnerable to the solar radiation variability, due to the influence on overall performances caused by the mismatch with compressor speed. The phase-change process of the working fluid should occur in quite stable conditions, while weather, and thus PVT temperature, may change rapidly. Therefore, complex control strategies under unstable weather conditions are necessary, as well as the use of a variable-speed compressor. The direct evaporation of HP refrigerant inside PVT collector avoids the use of any anti-freeze mixture, leading to better heat transfer coefficients and lower PVT operating temperatures, thus lower thermal losses towards the environment. On the contrary, particular attention is necessary to avoid very low operating temperatures, with possible collector frosting, moisture formation and consequent performance reduction or permanent damages [68]. In this sense, the choice of a suitable refrigerant able to meet satisfactorily both solar collector and HP requirements is a crucial point, that slowed down the diffusion of direct-expansion systems [53]. A further limit for single-source DX-PVT-SAHP systems is cooling production inverting the machine cycle, since the solar collector is unable to discharge heat in ambient during the day. In general, the fabrication simplicity and its low cost made DX-SAHP an interesting technology for reducing fossil fuel consumption in the domestic context, where cooling needs are limited. Despite this, a large number of disadvantages, with a particular focus on its poor performances under unstable weather conditions, are the cause of the recently reduced interest in DX-PVT-SAHP.

On the other way, indirect-expansion PVT-SAHP systems represent a diffused solution to several problems affecting direct-expansion systems, such as unsteady phase-change process, variable weather and temperature conditions, fluctuating performances and risks of wet-refrigerant entering in the compressor. The IDX-SAHP configuration allows a more flexible arrangement of system sub-components, thus the employment of thermal storage for solar energy or load management. The principal advantage of IDX-PVT-SAHP systems is the more stable heat gain from the solar side, since the refrigerant evaporates in a water-to-gas HX under more stable conditions compared to the direct-expansion inside the PVT collector, with lower dependence on weather conditions. Moreover, the presence of the intermediate HX allows shortening refrigeration lines, reducing refrigerant mass, with economic and environmental benefits. Indirect-expansion configuration also allows taking larger advantage from the integration of a second source, that may be exploited independently or simultaneously. Dual-source IDX-PVT-SAHP systems are the most feasible solution in climatic contexts where cooling needs are relevant, being able to cover all the building thermal needs. Those systems are also more suitable to be coupled with ground-source HP, which are very popular in heating-dominated regions, where air-source HP systems are less diffused.

In terms of performances, experimental research works on DX-PVT-SAHP showed average COP between 2.7 and 7, depending on operating conditions, generally registered during 1-day or few-days experiments in favourable environ- mental conditions. Those results are on average higher than indirect-expansion systems, which report average COP between 2.3 and 4.5 according to the above-mentioned studies, but are often measured during long-term experiments. These data underline the potentiality of direct-expansion systems in terms of performances, but the lack of long-term experimental data is likely due to intrinsically unstable performances in various environmental conditions, which limits their applications. In this sense, HP design requires particular consideration to the management of such an aleatory heat source as solar energy. Variable-speed compressors are preferable, especially in direct-expansion systems, while the choice of proper refrigerant is mainly influenced by system configuration (direct- or indirect-expansion), operating conditions (evaporating and condensing temperature) and environmental reason. R410A and R134a are the most diffused refrigerants for small and medium residential applications, but the progressive phase-out of HFC refrigerants in the next years opens the research to natural refrigerants, like propane and carbon dioxide.

Regarding PVT collectors, among the several technologies investigated in decades, the flat-plate collectors with direct lamination of PV cells over roll-bond absorber guarantees the best compromise among efficiency, reliability, manufacturing complexity and cost. Uncovered PVT collectors are preferable when the aim is to increase electricity production for self- consumption, while covered PVT is more suitable to maximize the thermal yield, and in particular, heat-pipe absorber constitutes a promising option in cold climates. The integration with HP systems is confirmed to enhance both electric and thermal performances due to the active cooling, which is relevant in both direct- and indirect-expansion system configurations.

The adoption of another heat source in combination with solar energy is fundamental to guarantee continuous system operations and allows to cover cooling needs in temperate and hot climates. Air-source HX can be easily integrated with PVT-SAHP systems due to their flexibility and cost-effectiveness, making them ideal for hot and temperate climates, as well as for retrofit intervention. PVT collectors and ground-source HPs are a suitable solution in colder countries where ground-source HP systems are more cost-effective than air-source technologies. These two heat sources can be integrated in series and parallel on the same water circuit, according to the different purposes: HP performance enhancement or boreholes regeneration.

The last key component of a PVT-SAHP is the energy storage, which is pivotal both for the proper operation of the system and to reduce the mismatch between solar energy generation profile and building load profile. In this sense, water thermal energy storages are deeply employed in PVT-SAHP systems, confirming the importance on both the source side and user side. When interposed between PVT and HP, water thermal storages may increase solar heat supply stability, solar energy production and HP performances. On the contrary, WTS on the user side allows increasing solar energy self-consumption, limiting start-stop HP cycles. Electrochemical storages are widely diffused on PVT DC-side to increase electricity self-consumption, while PCM storages are promising but still not sufficiently investigated.

In conclusion, regarding specific design rules of the whole PVT-SAHP system, the analysis carried out underlines that is hard to define reference sizing criteria, since climatic conditions and building loads strongly affect the ratio among the HP rated power, the PVT area and the storages' size. As a general indication, it is commonly accepted that the PVT area must be defined to cover the thermal load of the building in the month with the highest solar radiation, to avoid hot water overproduction. The size of the HP must be instead defined according to building peak thermal load, without considering the PVT contribution, to be sure that the system works properly also with scarce solar radiation. The optimal technology and size of the energy storage must be chosen according to design objectives. WTS combined with advanced control logic or simple electrochemical storages is indicated to increase PV electricity self-consumption, to minimize the amount of electricity exchanged with the grid if sized to store energy on daily basis. To maximize solar energy exploitation is always preferable to adopt WTS on the solar circuit for direct user needs (DHW storage) or HP use (hot source).

6. Conclusions and future perspectives

PVT-SAHP systems represent a very interesting solution for the nZEB design, being able to cover all the building thermal needs with a high share of RES. Overall energy performances are comparable and even better than those of con- conventional air-source and water-source systems. The integration of PVT collectors and HPs improves the performance of both sub-systems, increasing solar energy exploitation and HP efficiency, while reducing defrosting cycles in air- source HPs and borehole depletion in ground-source HPs; in addition, it extends the penetration of vapour-compression HP systems in both heating- and cooling-dominated regions.

Among the several available PVT-SAHP configurations, dual-source indirect-expansion systems represent the most promising solution to cover all the building thermal needs (i.e. heating, cooling and DHW), being an evolution of single-source and direct-expansion systems, without the main drawbacks that limit their applicability. Moreover, the adoption of flat-plate PVT collectors fabricated with direct-lamination of PV cells on the thermal absorbers appears a very interesting solution from the energy and cost point of view. Furthermore, water thermal storages for direct PVT heating and for heating/cooling building purposes and load-matching advance control systems allow reaching high levels of performance and reliability. The latter goes hand in hand with system complexity, thus overall cost. However, few authors provided a complete cost analysis, making it difficult to compare different solutions from the economic point of view. Detailed economic analyses are desirable to properly evaluate the cost-effectiveness of PVT-SAHP systems with respect to conventional HVAC solutions, even if their overall performances are promising and the scientific research continues to make progress in the field of sub-system integration, manufacturing techniques and control logic.

In addition, further effort is needed to increase the TRL (Technology Readiness Level) of dual-source HP and PVT collectors with direct lamination, to optimize their performance and minimize the cost. Furthermore, more experimental works are also needed to demonstrate the actual performances of the whole system in real case-study buildings, also comparing different sizing criteria according to climatic conditions and building loads. At the same time, ad additional effort is desirable in the development of specific tools able to properly model each component of the system and the system itself as a whole. PVT modelling in TRNSYS is still mainly based on solar thermal collectors with the PV layer added to the front. An upgrade related to advanced PVT layouts reviewed in the paper is required to better simulate the performance of PVT-SAHP configurations. Such actions are pivotal to support the further development and market penetration of PVT-SAHP technology in the building sector, where its application potential is huge.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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