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Photovoltaic-thermal solar-assisted heat pump systems for building applications: A technical review on direct expansion systems

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ABSTRACT

Buildings have a crucial role in global energy consumption and the release of greenhouse gases, especially due to their heating, cooling, and hot water systems. This study examines the incorporation of photovoltaic thermal (PV/T) and heat pump (HP) technologies, with a specific emphasis on their joint utilization in solar-assisted heat pump (SAHP) systems for enhancing building energy efficiency. The study conducts a thorough examination of contemporary literature to evaluate the effectiveness, feasibility, and performance metrics of PV/T-SAHP systems. Notable progress has been made by incorporating hybrid PV/T collectors, which can produce both electricity and thermal energy at the same time. This has led to enhanced system efficiency and increased reliability in operation. SAHP systems can be classified into numerous configurations, including direct expansion (DX) and indirect expansion (IDX) systems. Their performance under various climatic situations is thoroughly assessed. Concerning the direct expansion systems, the key numerical findings from the papers available in the scientific literature are summarized and discussed. The review highlights the capacity of PV/T-SAHP systems to improve energy efficiency, diminish carbon footprints, and promote sustainability in building applications. Identify future research directions to enhance system design, integration, and performance for wider implementation in low-carbon building initiatives.

1. Introduction

Buildings account for 20 % of the total energy consumption in underdeveloped nations and 40 % in wealthy nations, respectively, making them very energy-intensive [1]. Energy consumption is predicted to continue rising quickly as living standards and building service levels both increase [2,3]. Depending on the climatic zone and kind of structure, space cooling, space heating, and domestic hot water (DHW) often account for 40–60 % of building energy demand. The earth's sustainability is threatened by the massive energy consumption and greenhouse gas emissions that result from the fossil fuel-dominated energy system. Fighting global warming and maintaining low-carbon societies depend heavily on energy conservation and emission reduction in buildings, particularly in the areas of heating and cooling systems [4,5]. Building energy efficiency may be achieved by a range of strategies to meet the standards set forth in the building performance assessment, such as the well-recognized low-energy building [6], low-carbon building [7], net-zero energy building [8], carbon–neutral building [9], etc. In addition to improving the thermal performance of the building envelope, two types of actions are inexorably included into all these sophisticated concepts: new energy-efficient heating, ventilation, and air conditioning (HVAC) systems [10].

In addition, the EU created the Green Deal, which seeks to make the EU's economy more carbon–neutral and sustainable. The Green Deal includes renovating at least 35 million structures in the EU by 2030, which will enhance their energy efficiency and lower their carbon

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Abbreviations: ASHP, Air Source Heat Pump; ANN, Artificial Neural Network; AI, Artificial Intelligence; BIPV/T, Building Integrated Photovoltaic/Thermal; CFD, Computational Fluid Dynamics; CO2, Carbon Dioxide; COP, Coefficient of Performance; DHW, Domestic Hot Water; DX-SAHP, Direct Expansion Solar-Assisted Heat Pump; EER, Energy Efficiency Ratio; FPV, Fresnel Photovoltaic; FPV-SAHP, Fresnel Photovoltaic Solar-Assisted Heat Pump; GWP, Global Warming Potential; HCFCs, Hydrochlorofluorocarbons; HFOs, Hydrofluoroolefins; HP, Heat Pump; HX, Heat Exchanger; IDX-SAHP, Indirect Expansion Solar-Assisted Heat Pump; MHPAs, Micro Heat Pipe Arrays; NEER, Net Energy Efficiency Ratio; ODP, Ozone Depletion Potential; PCM, Phase Change Material; PCE, Photoelectric Conversion Efficiency; PV, Photovoltaic; PV/TAE, Photovoltaic/Thermoacoustic Energy; PV/T-SAHP, Photovoltaic-Thermal Solar-Assisted Heat Pump; RMS, Root Mean Square; SAHP, Solar-Assisted Heat Pump; TEG, Thermoelectric Generator; VFD, Variable Frequency Drive; ZEB, Zero Energy Building.

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footprint. Indeed, the construction industry significantly influences energy usage and greenhouse gas emissions in the EU. Nonetheless, the EU intends to minimize buildings' energy consumption and carbon footprint, making them more sustainable and ecologically friendly, by implementing energy-efficient building designs and supporting renewable energy sources [11].

Due to these incentives and advertising, the heating, cooling, and domestic hot water industries have seen a considerable market change. Remarkably, there have been significant increases in renewable efficiency technologies (such as pellet heating systems, heat pumps, solar thermal, etc.) [12].

Over the last several years, there has been a notable rise in the proportion of renewable energy used for heat and electricity generation, with a simultaneous reduction in the use of fossil fuels. Heat Pumps (HP) have the potential to decrease the primary energy consumption from fossil fuels in the heating and cooling sectors. The most often utilized HP technologies, air-source, and water-source, are not exclusively the optimal answer in terms of efficiency and prices, therefore integrating heat pump and Photovoltaic (PV) and photovoltaic/thermal (PV/T) technologies [13,14] have become popular and extensively researched renewable energy systems in recent years owing to their broad range of applications. The advantages and disadvantages of PV/T technologies are briefly outlined to evaluate their strengths and weaknesses.

The main objective of this study is to carry out a thorough examination of the current state of literature on photovoltaic thermal (PV/T) and heat pump systems, with a specific emphasis on their integration and performance. To bridge the gap in the literature, the objective of the review is to assess the effectiveness and feasibility of Direct expansion PV/T and design of PV/T- solar assisted heat pump (SAHP) components in building applications. The study aims to ascertain the benefits, drawbacks, and potential of these systems in mitigating energy usage and greenhouse gas emissions by examining many research publications. The technique entails a methodical evaluation of the performance parameters, economic viability, and environmental implications of single-source and dual-source PV/T and heat pump technologies through a comparative analysis. This work distinguishes itself from other review publications by focusing exclusively on PVT systems in conjunction with heat pumps, while considering various models. Instead, it focuses solely on the Direct Expansion PVT and heat pump system. Moreover, concerning the direct expansion systems, the key numerical findings from the papers available in the scientific literature are summarized in Tables and discussed. The objective is to provide a comprehensive and comprehensible analysis for readers with a specific interest in this particular arrangement.

2. Solar-assisted heat pump (SAHP)

The SAHP systems exemplify an advanced utilization of renewable energy technology for heating purposes. Solar energy is effectively captured in these systems using several types of solar collectors, such as flat-plate and concentration collectors and the concept consists of solar collectors, which may be either solar thermal collectors or hybrid Photovoltaic/Thermal (PV/T) systems, providing heat to the evaporator. Solar collectors can provide thermal energy that can be utilized for space heating, water heating, steam generating, or stored in thermal storage.

The solar energy that is gathered acts as the main heat source for a heat pump, which is a device specifically designed to transport heat from lower temperature sources to higher temperature sinks. SAHPs utilize solar energy to generate heat at higher source temperatures (inlet temperature of the evaporator), resulting in improved system efficiency.

In order to maintain a consistent and dependable heat supply, as any HP system also SAHP systems might include thermal storage devices, which enable the storing of surplus thermal energy produced during periods of intense solar radiation. Subsequently, this accumulated energy can be harnessed during periods of reduced sunshine or during nighttime. Moreover, SAHPs have the capability to function as hybrid systems, integrating solar energy with additional environmental heat sources such as ambient air or ground heat. This hybridization enhances the efficiency of the system, especially in areas where there are seasonal fluctuations in solar energy. A greater evaporative temperature leads to a decrease in power consumption and a rise in HP performance [15], while also improving the efficiency of heat extraction from solar collectors [16].

Furthermore, the incorporation of HP and solar technologies enables the resolution of several technical constraints encountered in independent solar thermal systems, such as reliance on climate and sun availability [17], substantial heat losses, poor efficiency, and challenges in achieving high supply temperatures during winter [18]. Heat pumps (HPs) may utilize the low temperature energy generated by solar collectors, they can also use a supplementary heat source when solar radiation is low or unavailable. This allows them to provide high-temperature energy for home applications without the need for a backup system.

The first idea of SAHP was introduced by Sporn and Ambrose in 1955 [19], and its significance grew in the 1970s [20]. Here we can address to the Solar-Assisted Heat Pump (SAHP) several advantages:

(i) enhanced efficiency of the technology, (ii) cost-effectiveness and installation flexibility, and (iii) improved utilization of solar radiation, thereby increasing its adoption in residential settings [21]. Geothermal heat pumps may also benefit from an increase in evaporative temperature from the regeneration of the earth via extra solar energy [22].

Another in-depth analysis was conducted on the impact of solar collector area, storage capacity, and the optimum design of various components on energy performances [23]. The use of variable-speed compressors facilitated improved alignment between power and solar gains across various weather conditions [24], while the advancements in the refrigerant sector have significantly benefited SAHP systems, resulting in improved performance, efficiency, and environmental sustainability. The solar collector often utilizes fluid (Refrigerant), such as air, water, glycol, or oil, as a medium for heat transmission and they have various channel forms and flow patterns. Both air and liquid can be utilized in the identical collector. The selection of the working fluid is done meticulously, considering the solar radiation in the specific geographical location, the heat capacity of the fluid, the design configuration, and the temperature range.

Recent advancements in refrigerant technology have led to the creation of novel refrigerants that possess reduced global warming potential (GWP) and ozone depletion potential (ODP). These new refrigerants are more ecologically sound when compared to conventional refrigerants like chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs).

Contemporary refrigerants, such as hydrofluoroolefins (HFOs) and natural refrigerants like CO2, ammonia, and hydrocarbons, provide superior thermodynamic qualities that enhance the coefficient of performance (COP) of heat pumps [25]. The use of carbon dioxide, for instance, as working fluid in HPs has been widely investigated in the literature [26,27], especially for applications in electric mobility [28,29]. SAHP systems have the capability to achieve greater efficiency in transmitting heat from the solar collectors to the intended heating or cooling application. under addition, novel refrigerants have been developed to function well throughout a wider spectrum of temperatures, hence improving the versatility and effectiveness of SAHP systems under different weather circumstances. Furthermore, these enhancements enhance the durability and dependability of the systems, hence decreasing the need for maintenance and lowering operational expenses.

The utilization of sophisticated lubricants that are compatible with contemporary refrigerants has further boosted the efficiency of compressors and other components within the system. This has resulted in decreased energy consumption and improved overall system performance. To summarize, improvements in refrigerant technology have greatly enhanced the performance of SAHP systems, resulting in increased efficiency, environmental friendliness, and versatility for many applications and climates [30,31].

2.1. Photovoltaic-thermal solar-assisted heat pumps (PV/T-SAHP) component design

Solar photovoltaic/thermal systems, which originated in the 1970 s, have the advantage of being able to harness a greater amount of incoming sunlight compared to PV cooling systems. A solar collector is connected to a photovoltaic panel to remove surplus heat from the module and lower the temperature of the cells, hence enhancing the efficiency of the cells. The system generates electrical power while simultaneously functioning as a thermal absorber. The solar thermal collector is categorized based on the kind of fluid used for heating, which can be either liquid or air.

The hybrid photovoltaic-thermal technology offers a compelling option for simultaneously generating heat and electricity. It outperforms the separate production of traditional photovoltaic and solar thermal systems in terms of renewable energy output of installed collectors [32,33].

Regrettably, the use of hybrid solar collectors encounters a significant limitation in the operational temperature, particularly due to climate conditions, such as in regions with high latitudes and during the winter season. As a result, they are unable to fulfill the complete heating need. Conversely, the combination of PV/Ts with DHW storages has an optimistic impact on the output of PV cells due to the elevated operating temperature. This effect is particularly pronounced during periods of intense solar radiation, low water usage, or when using covered PV/T systems [34].

By integrating the PV/T system with HPs, it becomes possible to utilize solar energy to meet thermal requirements while simultaneously keeping the PV cells at a low temperature [35]. Heat pumps may utilize the thermal energy generated by PV/T systems to meet the energy needs of buildings [36].

Additionally, the electricity generated by PV/T systems can be used to power the HP, resulting in a reduction in overall energy consumption [37]. In this particular field, the proportion of renewable energy generated and used on-site experiences a rise [38], resulting in advantages in terms of a decrease in CO2 emissions [39]. Simultaneously, the use of active cooling for PV cells results in improved efficiency for both PV/T systems and HPs, compared to using these systems separately [40]. This leads to a reduced power consumption, as well as the extraction of heat from the environment and roof area, resulting in energy savings [41]. By putting photovoltaic thermal (PV/T) systems on the roof of a building, they may harness solar energy to generate electricity and capture heat from the roof and its surroundings. This dual functionality aids in the cooling of the roof, hence diminishing the necessity for supplementary cooling equipment and resulting in total energy conservation. As a result, the building's power consumption is decreased because of the effective control of solar energy and heat extraction.

The PV/T-SAHP systems described demonstrate significant progress in energy efficiency compared to traditional SAHP systems that depend on solar thermal collectors and basic air-source HPs. This has been demonstrated by numerous studies over the past decade, such as, for instance [42,43].

PV/T-SAHP systems combine photovoltaic (PV) and thermal technologies, utilizing the dual capability of solar panels to produce energy and absorb heat concurrently. Rossi et al. [44] conducted a comparison of the three solutions listed above in various climatic circumstances. They found that PV/T-SAHP had higher electric efficiency and superior performance in terms of primary energy consumption compared to traditional SAHP or basic air-source HP.

Other researches evaluated the coefficient of performance (COP) of air-source HPs and dual-source (air and solar) PV/T-SAHP systems and found similar results [45,46].

Various degrees of integration between the heat pump and the solar collector have been suggested in academic literature. Reviews on SAHP are comprehensive and thorough, reflecting the wide range and profound nature of the topic. A recent and extensive review work on this issue was authored by Mohanraj et al. [47]. The authors conducted a thorough review of SAHP systems in a two-part paper. In the first part, they examined previous studies on SAHP system configurations, modeling, and development. In the second part, they categorized the application areas of these studies, highlighting their limitations and identifying future research tasks.

The present review paper focuses on PV/T-SAHP systems designed for low water-temperature applications, which are widely utilized in building applications. Thus, the focus is on utilizing heat pumps that are combined with water-based flat plate PV/T collectors for water heating and cooling. These PV/T collectors are considered the most efficient technology for PV/T systems and are also the most practical choice for HVAC systems [48].

The performance of PV/T-SAHP systems is closely tied to the advancement of each individual part, as well as their proper integration and configuration. The subsequent sections provide the current advancements in the primary components of the PV/T-SAHP system, highlighting typical design decisions and the most innovative ideas discussed in recent research. It is essential to emphasize that the appropriate design of every component and its systematic integration within the complete PV/T-SAHP system should be customized to the individual characteristics of each application scenario, including meteorological conditions, building thermal loads, and other contextual considerations [49]. Additionally, in the subsequent section, we will find a review paper discussing the various types of PV/T panels.

Chen et al. [50] performed a performance analysis on a heat-pipe solar photovoltaic/thermal (HPS PV/T) heat pump system. This system combines heat pipes with PV panels to produce electricity and thermal energy at the same time. Their research showed that combining a heat pump with the HPS PV/T collector greatly enhances the efficiency of converting sunlight into electricity. The mathematical model demonstrated that higher levels of solar radiation, ambient temperature, and PV backboard absorptivity result in an improved coefficient of performance based on the thermal efficiency (COPth) of the system. In contrast, the COPth was seen to change due to parameters such as the supply water temperature in the condenser, PV packing factor, and heat pipe pitch. Moreover, the rise in solar radiation and packing factor resulted in an elevated coefficient of performance for both thermal and electrical performances (COPPV/T). Conversely, COPPV/T declined when the ambient temperature, supply water temperature in the condenser, and heat pipe pitch increased.

Jian Yao et al. [51] presented a new and innovative Photovoltaic-Thermal (PV/T) module that is specifically developed to improve the co-generation efficiency in building sectors. The PV/T module underwent manufacturing and testing as part of a solar-assisted heat pump system to assess its thermal, electrical, and hydraulic performance. The results demonstrated notable enhancements compared to standard PV/T technologies. The experimental findings demonstrated an average electrical efficiency of 17.93 % and a thermal efficiency of 109.4 %. Additionally, the system's Coefficient of Performance (COP) was measured at 5.43, which is 42.9 % greater than that of a standard air source heat pump water heater. The PV/T module exhibited improved control over temperature uniformity in comparison to a single PV module, effectively maintaining an operational temperature differential of less than 0.7 °C. The system's yearly carbon dioxide (CO2) emissions for electricity and hot water amount to 565.8 kgCO2, which is just 11.41 % of what existing technologies produce. Additionally, the roll-bond panel as shown in Fig. 1, facilitates the absorption of heat from the surrounding air. Although distributed co-generation in buildings offers advantages, the implementation of large-scale applications is hindered by the features of refrigerant two-phase flow. This calls for more study on mass flow distribution and the reduction of flow resistance in big

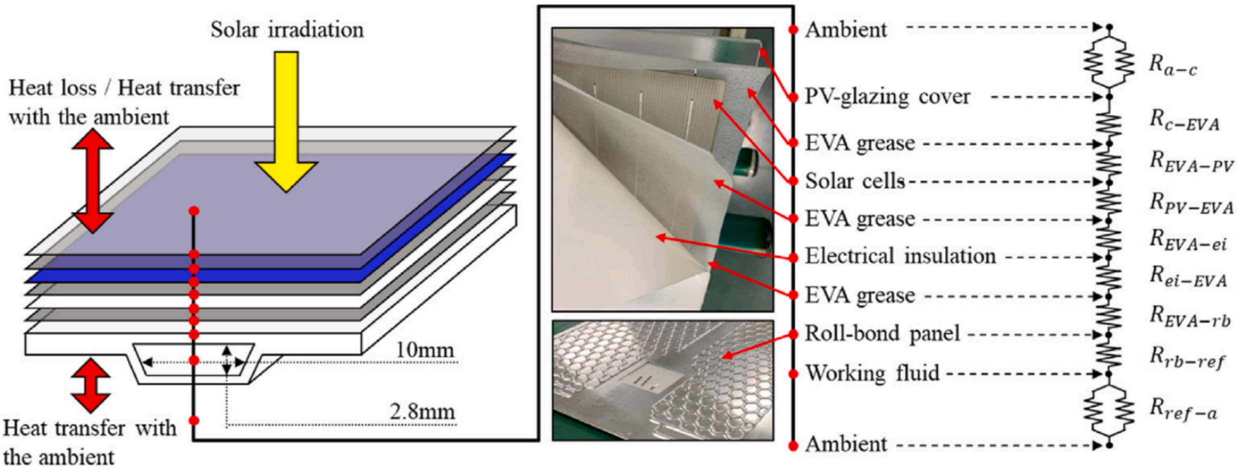

Fig. 1. The multilayer structure of the PV/T module and its thermal resistance model, from [51].

systems.

Abbas et al. [52] examined the operating efficiency of a solar direct-expansion heat pump system that used both photovoltaic/thermal (PV/T) and solar thermal collector (TC) as evaporators. The goal was to evaluate the system's capacity to produce both high thermal energy and power at the same time. The hybrid PV/T-TC heat pump system's performance was assessed under actual climatic circumstances using R134a as the heat transfer fluid for its safety and stability, via both computational and experimental methods. The results showed better thermal efficiency and coefficient of performance (COP) in comparison to a single PV/T system and solar thermal collector. The PV/T-TC heat pump system demonstrated an average electrical efficiency of 14.08 %, thermal efficiency of 66.71 %, and COP of 6.11 in the experiments. The comparative investigation showed that the PV/T-TC system had superior electrical and thermal efficiency, indicating its potential suitability for use in residential structures. The PV/T-TC system showed an 86.1 % primary energy saving efficiency due to its average electricity output of 0.86 kWh/day and thermal energy production of 6.35 kWh/day, highlighting its efficacy.

In their recent study, Abbas et al. [53] conducted an economic evaluation and yearly performance analysis of a new series-coupled PV/T and solar thermal collector system combined with a solar direct expansion heat pump. This research attempted to improve upon a hybrid refrigerant-based PV/T-TC system with a heat pump presented in a previous study [52] to generate electricity and high-grade heat simultaneously. It focused on addressing the current gaps and limitations in PV/T-TC systems. A 0.5234 kW heat pump prototype, including the 1st and 2nd laws of thermodynamics, was built, and tested in Karachi, Pakistan, together with a 3.5 m2 PV/T-TC area. The experimental findings demonstrated mean daily efficiencies for electrical, thermal, total energy, and exergy of 14.08 %, 60.12 %, 74.20 %, and 18.12 %, respectively. The system can produce 303.51 kWh of electricity and 3213.12 kWh of heat energy per year, with an average COP of 5.68. The economic analysis showed that the hybrid refrigerant-based PV/T-TC system has a payback time of 5.20 years, while the PV/T aided direct-expansion heat pump system has a payback period of 7.15 years. The experimental data closely matched the simulated findings, with an average relative error of 3.30 %.

Song et al. [54] compared the efficiency of direct-expansion solar-assisted heat pumps using three types of PV evaporators, Fresnel PV (FPV), hybrid FPV combined with a thermoelectric generator (TEG), and standard PV evaporators. The goal was to examine the most efficient evaporator design. The study investigated the effect of incorporating a thermoelectric generator (TEG) into a photovoltaic system. The TEG turns heat from the photovoltaic panel into electrical energy, but it also raises thermal resistance, which hampers the cooling of the photovoltaic panel. The comparison examined electrical efficiency, coefficient of performance (COPPV/T), overall efficiency, and exergy efficiency across different levels of solar irradiation. The FPV-SAHP demonstrated superior performance compared to the standard PV-SAHP, with both FPV-SAHP and FPV/TEG-SAHP surpassing it in all criteria. The study also projected and examined how ambient and water temperatures affect the FPV-SAHP system.

Zhou et al. [55] created and verified a numerical simulation model for a DX PV/T HP system that includes a microchannel PV/T evaporator. The system's performance was evaluated using a combination of experimental and numerical simulation studies. The experimental data revealed an average electrical efficiency of 13.1 %, a thermal efficiency of 56.6 %, and a total energy efficiency of 69.7 %. The simulated results showed a modest decrease, with electrical efficiencies measuring at 13.7 %, thermal efficiencies at 55.0 %, and overall energy efficiencies at 69.1 %. The Coefficient of Performance (COP) exhibited a correlation with solar radiation, with average values of 4.7 (experimental) and 5.0 (simulated) on the testing day. The largest variation observed was 7.2 %. The microchannel tube demonstrated greater performance in comparison to conventional systems, principally attributed to its improved efficiency resulting from distinctive manufacturing characteristics.

When comparing solar thermal modules to PV/T systems, solar thermal modules have a higher thermal energy collection capacity. In contrast, PV/T systems integrate the production of electricity and heat, leading to enhanced efficiency of the solar cell [56].

Various arrangements of solar collectors and heat pumps may be used to achieve different combinations of solar-assisted heat pump (SAHP) systems. The parallel and series configurations are well recognized, with the former being more durable and dependable for simpler hydraulic connections, design, and optimization. However, the latter choice is more sophisticated and offers superior performance [18]. Dual-source systems, which combine solar energy with another heat source, were quickly acknowledged as promising [57] and have since been extensively studied for their significant performance and energy-saving advantages compared to basic parallel and series setups [58].

2.2. *Different categories of the solar assisted heat pump systems (SAHPs)*

The categorization of the machine is determined by how it harnesses solar energy. This is a critical aspect of the PV/T-SAHP, since it directly impacts the system's performance and dependability. The upcoming chapter is divided into two categories: direct-expansion (DX) systems and indirect-expansion (IDX) systems. In DX systems, the PV/T collector functions as the HP evaporator. In IDX systems, a heat exchanger (HX) is placed between the PV/T collector and the HP. There is a distinction between single-source setups, which rely solely on solar energy as the heat source for the heat pump, and dual-source systems, which utilize another heat source in addition to solar energy. Fig. 2 presents a conceptual framework illustrating many analyzed choices.

SAHP systems are primarily categorized based on the mechanism by which solar energy assists in heating the pump. The items are:

i.Direct expansion solar assisted heat pump (DX-SAHP)

- Direct expansion photovoltaic-thermal solar assisted heat pump (DX-PV/T-SAHP)
- *Single-source DX-PV/T-SAHP*
- *Dual-source DX-PV/T-SAHP*

ii.Indirect expansion solar assisted heat pump (IDX-SAHP)

- Indirect expansion photovoltaic-thermal solar assisted heat pump (IDX-PV/T-SAHP)
- *Single-source indirect-expansion PV/T-SAHP systems*
- *Dual-source indirect-expansion PV/T-SAHP systems*

A concise overview of each categorization of SAHP systems is provided below inside each respective subsection.

The complexity of the system is also affected by the kind and subtype of the PV/T-SAHP. When analyzing a direct expansion system, it is necessary to take into account the flow of refrigerant in both liquid and vapor phases in the PV/T-evaporator. On the contrary, in an indirect expansion system, only the liquid phase needs to be addressed. Additionally, employing a dual-source approach adds complexity to the modeling process.

3. Direct expansion solar assisted heat pump (DX-SAHP)

The DX-SAHP system is an innovative integration of a solar collector and a heat pump. It is a distinct subtype within this category and is recognized as the initial configuration of a solar-assisted heat pump (SAHP). In this system, the refrigerant circulates through the solar collector as a unified unit. This design enables solar radiation to directly serve as a heat source for the evaporator, avoiding the necessity for any intermediate fluid. The solar collector-evaporator can be arranged in either an exposed or insulated configuration, with the choice determined by the collector's operating temperature in relation to the surrounding conditions. This method, thoroughly investigated by several researchers throughout the years [59,60], integrates conventional solar thermal collectors with heat pumps.

In another study, Song et al. [61] conducted a yearly study of a solar direct-expansion heat pump system with double condensing equipment for secondary electricity generation. Referring to prior research [54] that identified obstacles to heat dissipation and electricity degradation in solar systems due to thermoelectric generator installation, a new method was suggested. They used a complex system that combined solar technology with a heat pump system, incorporating thermoelectric generators and micro-channel heat pipes, along with a water-cooling condenser to cool the photovoltaic panels and aid in thermoelectric conversion. The study forecasted system performance on a yearly basis by using weather conditions from various latitudes and altitudes. The results showed increased electrical efficiency due to the greater power output from the TEG. In Hong Kong's warmer climate, the heating capacity grew, but the compressor usage also rose. In a case study regarding the municipality of Garze (China), outstanding electrical performance is shown because of improved irradiation and lower ambient temperatures, achieving monthly and yearly COPPV/T & net energy efficiency ratio (NEER) values of 9.9 and 8.0, respectively. The system showed significantly reduced operating costs and CO2 emissions in comparison to gas boilers, indicating a high potential for energy savings and emission reduction, with ratios varying from 1/4 to 1/3 and 1/3 to 1/2, respectively.

Zhou et al. [62] investigated experimentally the cogeneration performance of roll-bond-PV/T heat pump system with single stage compression during summer. The paper provides a detailed introduction to the roll-bond-PV/T (RB-PV/T) unit, which combines a solar module with a single-sided roll-bond evaporation heat exchanger. These components are laminated together. Indeed, their findings of the operational characteristics monitoring indicate that the system operated consistently and efficiently throughout daylight hours, demonstrating significant cogeneration performance. Their investigation showcased the substantial potential for practical implementation of the RB-PV/THP system on a wide scale in northern China.

Mohanraj et al. [63] investigated the application of artificial neural networks (ANN) in predicting the efficiency of direct expansion solar-assisted heat pumps (DXSAHP). By conducting experiments in Calicut, India, they created a new method for predicting DXSAHP performance

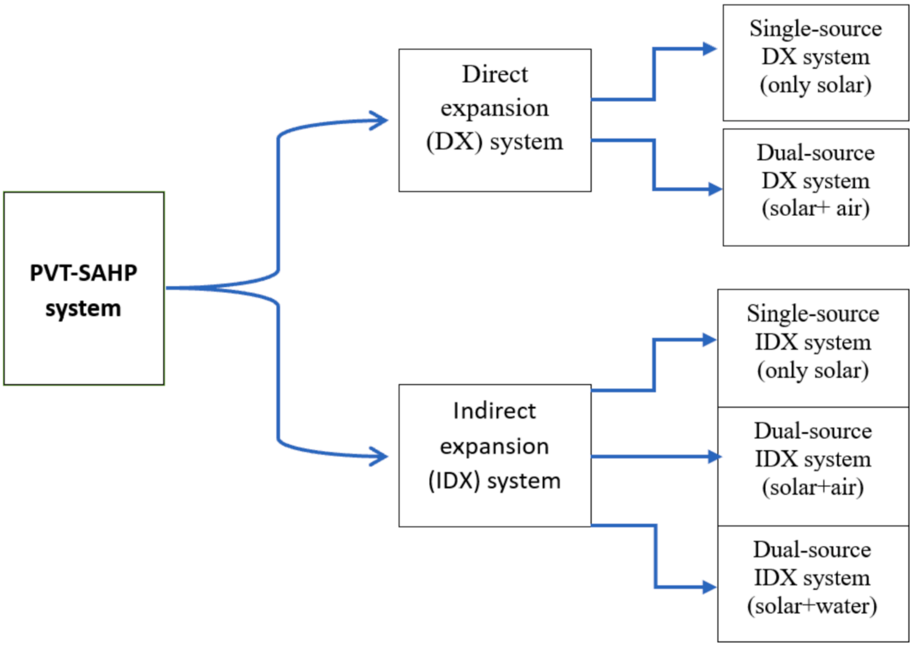

Fig. 2. Conceptual scheme of PV/T-SAHP system configurations.

by utilizing an Artificial Neural Network (ANN) model that employs the backpropagation algorithm. This model considers ambient conditions such as solar intensity and temperature. The findings demonstrated that employing the Levenberg-Marquardt (LM) algorithm with a hidden layer consisting of 10 neurons yielded the most significant correlation coefficients (R2) of 0.999, minimal root mean square (RMS) value, and a low coefficient of variance (COV). This confirmed the feasibility of utilizing Artificial Neural Networks (ANN) for predicting the performance of Direct Expansion Air-Source Heat Pumps (DXSAHP).

Han et al. [64] developed an adaptive proportional-integral control method (APCM) for a direct expansion photovoltaic-thermal heat pump (DX-PV/THP) system, to improve the speed of stabilizing superheat during start-up and continuous operation. They used a GA-BP neural network model and a mathematical model to compute refrigerant heat absorption. This allowed them to determine the electronic expansion valve (EEV) opening at start-up and predict the EEV opening during continuous operation. Evaluation of control performance was based on overshot and overshot duration % of superheat. Additionally, a comprehensive coefficient of heating and electricity generation (CHE) was established to evaluate system performance. Experimental testing in common foggy conditions showed enhanced stability of superheat, with a peak overshoot of 3.2 °C and a 27.54 % decrease in overshoot duration compared to traditional techniques. In residential and commercial settings, the average coefficients of performance were 3.51 and 3.16, while the photoelectric conversion efficiencies were 13.25 % and 13.78 %, respectively. The proposed Combined Heat and Electricity system achieved efficiency values of 34.92 % in family mode and 32.83 % in commercial mode, demonstrating the system's overall performance. This research improves the operational stability of DX-PV/THP systems in challenging settings, offering valuable information for optimization and management.

Also, Mi et al. [65] studied the operation performance and prediction of photovoltaic thermal heat pump system engineering in winter. They offered an original approach for arranging solar thermal modules in an array and a novel way of connecting the refrigerant pipeline in their study. The study highlights the need to improve the design of system integration and operation to enhance energy efficiency. It proposes the possible application of solar thermal heat pumps for clean district heating or home hot water, hence boosting energy-saving reconstruction. According to the authors, it is advisable to do more study on the correlation between internal operating parameters and climatic circumstances. This should include conducting longer operation simulations in several cities to improve our knowledge of how these findings might be used regionally.

Rabelo et al. [66] performed an economic study and design optimization of a direct expansion solar-assisted heat pump (DXSAHP). Simulations were performed by altering collector size, compressor size, refrigerant type, ambient conditions, and heating capacity using a mathematically verified model that incorporates lumped models for heat exchangers and a semi-empirical model for the compressor. The results demonstrate that enlarging the collector size improves the coefficient of performance (COP) while diminishing the collector efficiency. An economic study demonstrates that there exists an ideal size for the collector that minimizes the payback time. This optimal size is determined by several factors such as ambient conditions, choice of refrigerant, expenses, and heating capacity. The findings emphasize the economically optimal size of the collector for DXSAHP, which remains consistent regardless of the ambient circumstances. Case studies conducted in several cities have shown that the system's payback period ranges from 1.77 to 3.24 years, indicating its feasibility in varied weather conditions.

Liu et al. [67] performed a thorough examination of the life cycle energy, economic, and environmental factors associated with the direct-expansion photovoltaic-thermal (DX-PV/T) heat pump system. They analyzed the thermal and electrical performance of the system using MATLAB-based yearly simulations. They also assessed how the system's susceptibility to power generating mix and technology improvements. The results demonstrated significant benefits, such as a 9.67 % rise in yearly power production compared to conventional solar systems, along with an 88.21 % self-sufficiency rate. In addition, the DX-PV/T system exhibited a much-reduced environmental footprint, with a life cycle environmental effect of about 3–5 % in comparison to electric boilers. The environmental payback periods varied from 0.33 to 5.18 years, which were less than the investment payback periods of 2.49–5.21 years. This suggests that there is a possibility of reducing costs. Significantly, the environmental implications were influenced by electricity consumption during operation, highlighting the crucial need to reduce carbon emissions from the power grid and enhance system efficiency.

The DX-SAHP is primarily intended for the generation of domestic hot water (DHW) and is renowned for its straightforward design. The DX-PV/T-SAHP system utilizes one or more PV/T collectors as the heat pump evaporator, allowing solar energy to operate the machine. The heat pump refrigerant passes through the heat absorber of the PV/T collector-evaporator in this setup, removing heat as it undergoes a phase-change process.

Recently, there have been advancements in finding new methods for DX-SAHP systems to optimize the use of air and solar resources.

To classify these new techniques, DX-SAHP systems can be categorized as direct expansion single-source DX-PV/T-SAHP, direct expansion solar-air dual source heat pump (DX-SADHP), direct expansion solar-air parallel heat pump (DX-SA-DHP), and direct expansion solar-air serial heat pump, which is a modified version of the fundamental DX-SAHP systems.

The accompanying sections contain thorough research investigations on DX-PV/T-SAHP systems, including both single- and dual-source configurations. Table 1 summarizes the important works. The discussion centers on the most pertinent discoveries derived from these investigations.

3.1. Single-source DX-PV/T-SAHP

The single-source DX-PV/T-SAHP for water heating is the most basic and initial studied use of hybrid PV/T with HPs. Fig. 3 illustrates that the hybrid collector is the only energy source for the machine in this particular setup. The system has the capability to generate hot water at various temperature levels, depending on its design, for the purpose of space heating or domestic hot water (DHW).

However, it often does not have the capability to offer cooling in this form. Ito et al. [68] were pioneers in introducing a DX-PV/T-SAHP system for water heating, which utilized an improved hybrid collector. This system was developed as a result of a prior research study [92].

Experimental results indicate that the use of larger hydraulic connections resulted in decreased pressure losses and improved distribution of refrigerant throughout the PV/T. This led to an increase in the coefficient of performance (COP) of around 5–10 %.

Ji et al. [69] introduced a DX-PV/T-SAHP system designed for water heating. They created a model and conducted simulations to assess the temperature distribution throughout the evaporator. The model was also applied to mimic performances in varying climatic circumstances such as Tibet [93] and Hong Kong [94]; this was achieved by making appropriate enhancements to the PV/T collector, resulting in promising system performances Fig. 4.

Liu et al. [70] examined the efficiency of a solar-assisted DX-PV/T heat pump system, specifically analyzing how the area of the PV/T module affects system performance. They created an analytical model and confirmed its accuracy by comparing it with actual data in order to provide the most efficient system setup. The results suggest that increasing the ratio of the area of the PV/T modules to the theoretical displacement of the compressor (A/Vth ratios) improves the coefficient of performance (COP) and makes the system more suitable for cold areas. However, it also decreases the overall thermal performance. The effects of A/Vth (activation voltage) are influenced by temperature and

Table 1
Studies on direct-expansion PV/T-SAHP systems.

Ref.	Year	Study	Useful effect	Performances (COP)	Data type	Heat source
Song et al. [54]	2020	numerical	water heating	7.67 at 10 °C	parametric analysis	only solar
Song et al. [61]	2023	num. and exp	water heating	5.1–8	1-year analysis	only solar
Chen et al. [50]	2017	numerical	water heating	3.5–6	parametric analysis	only solar
Yao et al. [51]	2022	Experimental	Heating HP	Average system COP 5.43	parametric analysis	only solar
Zhou et al. [62]	2019	Experimental	water heating	6.16	during summer	only solar
Mohanraj et al. [63]	2009	AI& Experimental	water heating		winter months	only solar
Han et al. [64]	2023	Num, and exp	water heating	3.51–3.16	parametric analysis	only solar
Mi et al. [65]	2022	Experimental	Heating system	2.07–2.76	1-month(winter)	only solar
Sabrina et al. [66]	2019	Num, and exp(economic)	DHW	3–5.8	parametric analysis	only solar
Liu et al. [67]	2024	numerical (economic)	DHW	annual COP is 6.43	parametric analysis	only solar
Sajid Abbas et al. [52]	2022	Num, and exp	thermal and electricity	6.11	parametric analysis	only solar
Sajid Abbas et al. [53]	2023	Num, and exp	DHW, heating	annual COP is 5.68	1-year analysis	only solar
Zhou et al. [55]	2020	Num, and exp	space heating	experimental:4.7 – simulation:5	1-month	only solar
Ito et al. [68]	2005	Num, and exp	DHW, heating	COP:1.8–4.4	1-day experiment	only solar
Ji et al. [69]	2008	Num, and exp	water heating	COP:3.8–8.4, average:6.4	1-day experiment	only solar
Liu et al. [70]	2023	Num, and exp	DHW, heating	3.1 to 5.0	parametric analysis	only solar
Yao et al. [71]	2020	Num, Theoretical analysis	water heating	–	parametric analysis	only solar
Zhang et al. [72]	2017	Experimental	water heating	COP:3.03–4.37, average:3.66	1-day experiment	only solar
Zhou et al. [73]	2016	Experimental	water heating	COP:3.1–5.6, average:4.7	7-day experiment	only solar
Liang et al. [74]	2018	Experimental	hot water	max COP:3.1	7-day experiment	only solar
Li et al. [75]	2019	Num, and exp	water heating	COP:4.4–5.2	2-day experiment	only solar
James et al. [76]	2021	Experimental	hot water	max COP:7.4	parametric analysis	only solar
Chen et al. [77]	2011	Experimental	hot water	averaged COP:3.8–4.3–4	parametric analysis	only solar
Wang et al. [78]	2015	Num, and exp	heating and cooling	averaged COP: 2.5	parametric analysis	solar&air
Yubo Wang et al. [79]	2024	Num, and exp	building heating	COP:3–2.4	winter months	solar&air
Cai et al. [80]	2021	numerical	water heating	averaged COP: 2.4	parametric analysis	solar&air
Li et al. [81]	2022	num, Simulation analysis	hot water	COP:4.76	parametric analysis	solar&air
Cai et al. [82]	2017	numerical	hot water	average COP: 2.25–2.45–2.66	parametric analysis	solar&air
Fu et al. [83]	2012	Experimental	DHW	average COP: 3.32–4.01	1-day experiment	solar&air
Li and Sun [84]	2018	numerical	water heating	average COP: 3.10	monthly simulation	solar&air
Yao et al. [43]	2020	numerical	hot water	max COP 7.4	parametric analysis	solar&ground
Yao et al. [85]	2021	mathematical model	residential heating	COP:4.0 at -10C	parametric analysis	solar&air
Erdinc et al. [86]	2023	numerical	residential heating	COP improved by 22.6 %	parametric analysis	solar&air
Fang et al. [87]	2010	Experimental	DHW, heating and cooling	COP:2.75–2.85	2-hours experiment	solar&air
Bae et al. [88]	2023	num and experimental	heating and cooling	heating:3.54- cooling:3.31	long term measurements	solar&ground
Zhang et al. [89]	2022	Experimental	DHW, heating and cooling	average COP: 4.96	winter months	solar&air
Du et al. [90]	2021	Experimental	heating and cooling	average COP: 2.8–2.1–2	parametric analysis	solar&air
Du et al. [91]	2023	numerical	building heating	average COPh values1.42–3.44	parametric analysis	solar&air

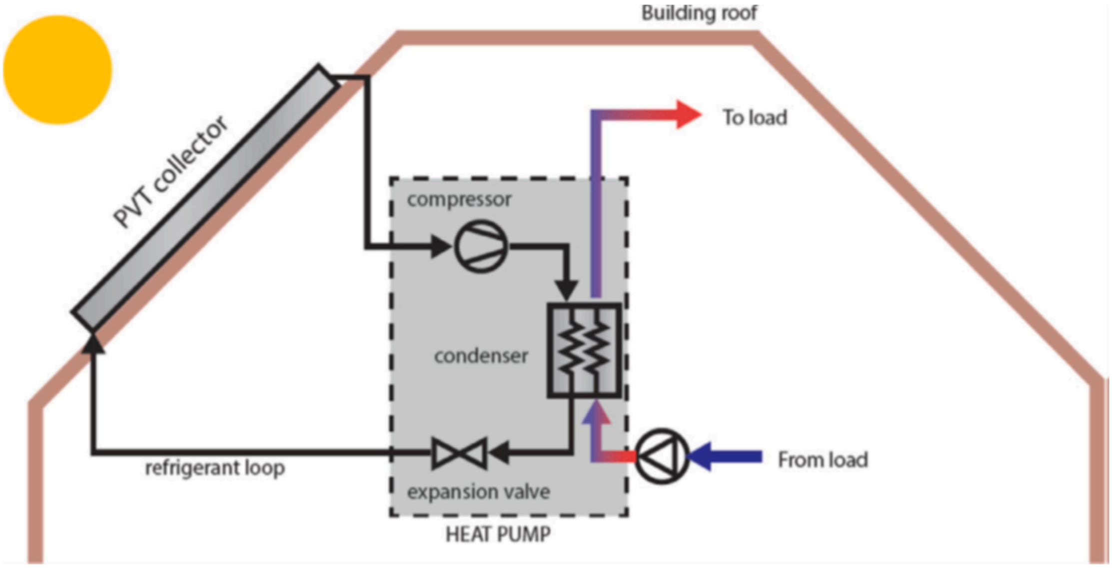

Fig. 3. Sketch from [49] of a DX-PV/T.

solar irradiation, indicating that sunny places tend to have higher ratios. The study suggests that for optimal functioning, an A/Vth range of 1.535 to 1.919 m2 h/m3 is recommended. This range demonstrates higher heating capabilities when compared to ASHP and flat plate collector (FPC).

Yao et al. [71] performed a comprehensive investigation, including theoretical analysis and practical examination, to determine the efficiency factor of two-phase flow channel designs in direct expansion photovoltaic-thermal collectors (PV/T evaporators). Theoretical investigation resulted in the creation of a hexagon-grid linked fluid channel

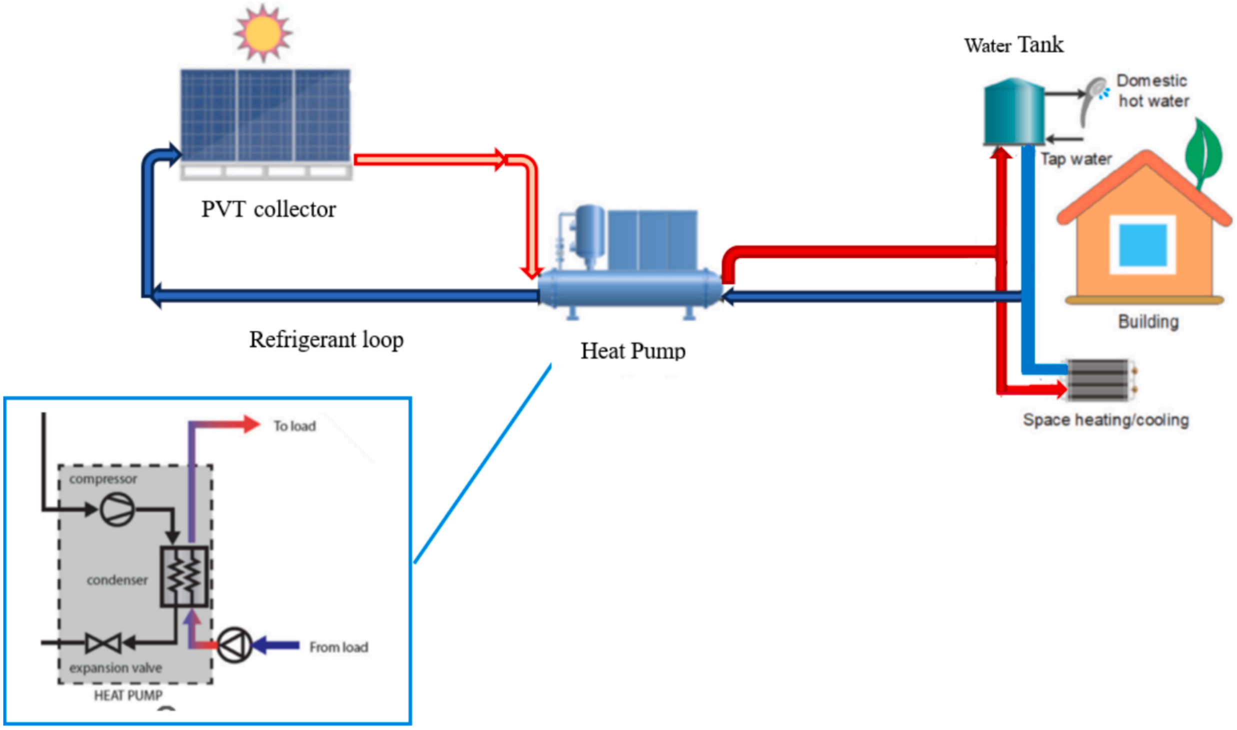

Fig. 4. General scheme of single-source DX-PV/T-SAHP.

unit with a one-way arrangement, leading to significant enhancements in temperature uniformity, thermal and electrical efficiency, and hydraulic behavior. The experimental results indicate that this approach has the capacity to substantially decrease the operating temperature of photovoltaic modules. The results demonstrate that hexagon and rectangle layouts provide better temperature distribution uniformity, but with the drawback of greater pressure loss. On the other hand, grid and linear topologies show the reverse pattern. The use of grid layout has

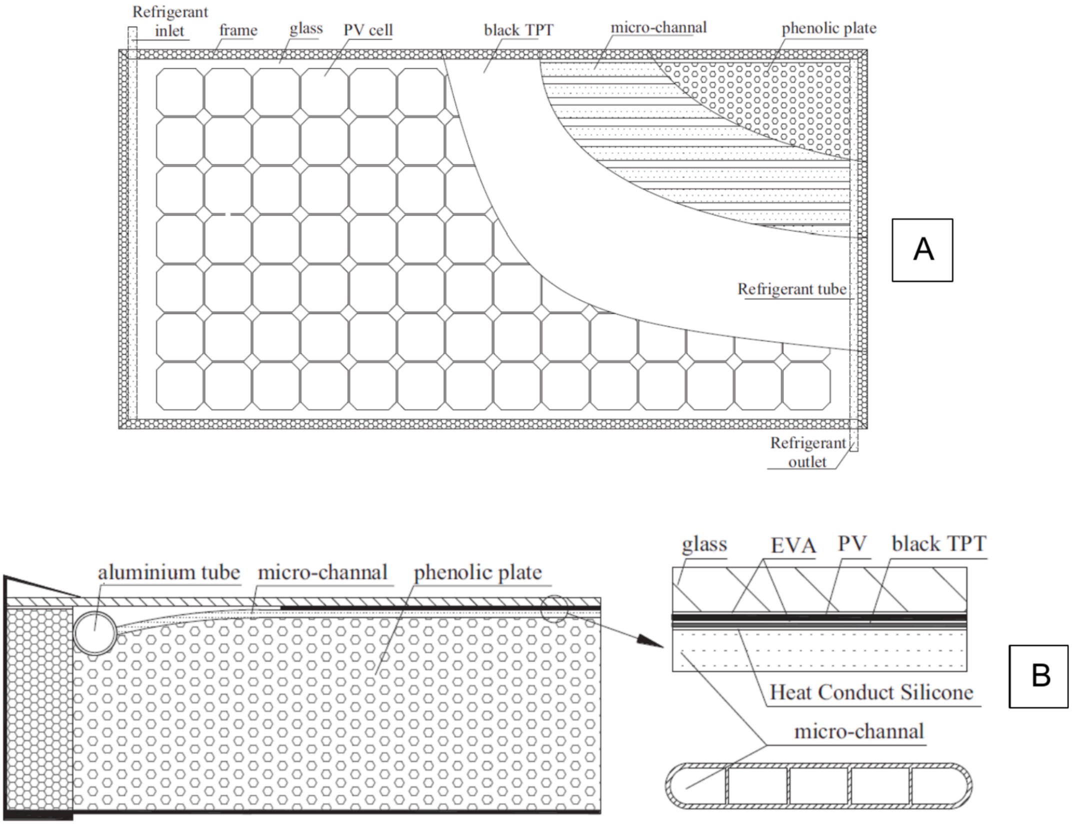

Fig. 5. (A) The structure of the PV/micro-channel-evaporator module (B) Sectional view of the PV/micro-channels-evaporator module, from [73].

been shown to be highly efficient in controlling the temperature of photovoltaic (PV) cells and improving their electrical efficiency. Efficiency factors for each unit type are derived theoretically, considering pressure loss using Computational Fluid Dynamics (CFD) modeling.

Zhang et al. [72] developed a novel photovoltaic/loop-heat-pipe system to support the HP system in producing hot water for residential use. The prototype operates in two distinct modes based on climatic circumstances and temperature requirements: the traditional DX-PV/T-SAHP mode and the loop heat pipe photovoltaic-thermal mode. The latter mode utilizes direct solar water heating during periods of high radiation. The average coefficient of performance (COP) achieved with DX-PV/T-SAHP showed good results. Additionally, the thermal and photovoltaic average efficiencies were greater compared to the loop heat-pipe PV/T mode. This indicates the advantages of coupling with a heat pump (HP). In their study, Zhou et al. [73] utilized a PV/micro-channel hybrid collector as an evaporator in DX-PV/T-SAHP systems to produce hot water illustrated in Fig. 5. The system demonstrated excellent performance in both PV/T and HP, achieving an average system COP of 4.7 over a 1-week experimental test conducted in northern China. Subsequent examination utilizing a suitable quantitative model [55] resulted in the optimization of the system in relation to PV/T efficiency, achieving an electric efficiency of 14.5 % and a thermal efficiency of 59.7 %. Additionally, the coefficient of performance (COP) was enhanced to a maximum value of 5.2 [95].

Liang et al. [74] combined a ventilated micro-channel PV/T façade system, which reduces heat transfer from the building, with a direct-expansion system for efficient hot water generation. The system demonstrated excellent performance in real-world testing settings. Real-time control of compressor frequency is essential in DX-PV/T-SAHP systems. Li et al. [75] devised a real-time integrated control technique to modify the working frequency of the compressor based on the current radiation levels. The suggested control technique demonstrated significant enhancements in PV energy generation and system COP compared to the utilization of a conventional demand-driven control strategy. James et al. [76] also emphasized the reduction of electricity exchange with the grid and achieved favorable outcomes in terms of energy efficiency. They accomplished this by utilizing a feedback-controlled variable frequency drive (VFD) compressor that operates based on the current load. Various numerical studies have examined the advantageous effects of active cooling on the electrical performance of PV/T collectors when used as an evaporator in DX-PV/T-SAHP systems [96] including under various climatic circumstances.Typically, the use of a single-source DX-PV/T-SAHP is common for generating hot water. However, there are a few instances documented in literature where PV/T collectors have been used as a condenser at nighttime [97,98].

Chen et al. [77] investigated on Nottingham, England to empirically examine the energy efficiency of a PV/T + HP system. This system utilized a glass vacuum tube PV panel and employed R134a as the working fluid. The study involved the construction of a tiny photovoltaic (PV) panel consisting of six glass vacuum tubes. These tubes were linked in series with an aluminum sheet and a copper tube (GPAC) sandwich, which served as the evaporator. This was accompanied by a compact heat pump system. The use of glass vacuum tubes effectively minimized heat dissipation from the photovoltaic (PV) panel to the surrounding environment, hence enhancing its thermal efficiency. The results suggest that the Coefficient of Performance (COP) of the heat pump system rises as radiation levels increase. Specifically, the COP ranges from 2.9 to 4.6 when radiation levels vary from 200 W/m2 to 800 W/m2. In addition, the article demonstrates that there is a reduction in COP when the condenser water supply temperatures are greater and when the condenser water flow rates are raised. This provides valuable information on how the system performs under various operating circumstances.

Kuang and Wang [99] conducted an experiment on a system where the PV/T-evaporator functions as a condenser during the night and saves cold water for daily usage. In a similar manner, Zhou et al. [100] conducted an experiment using a DX-PV/T-SAHP to lower the temperature of the cold storage facility at night, until ice was formed. The authors achieved a refrigeration performance, with an average daily Energy Efficiency Ratio (EER) ranging from 1.86 to 2.84, in various experimental tests [101,102]; however, this configuration necessitated a high condensation temperature (up to 80 °C) and a larger cold storage capacity (600 L) compared to the hot storage capacity (150 L) in order to meet all the cooling requirements during the daytime.

3.2. *Dual-source DX-PV/T-SAHP:*

Hence, the introduction of the direct expansion dual source heat pump was proposed to consistently harness solar energy and enhance the efficiency of the system. DX-PV/T-SAHP systems can incorporate a secondary heat source by utilizing a second evaporator that operates alongside PV/T collectors, as depicted in Fig. 6. The solar collector evaporator is an exposed apparatus specifically engineered to effectively harness heat from solar radiation and the surrounding atmosphere.

The inclusion of an extra heat source, typically air, enhances the efficiency of the system in unfavorable operating conditions, when the solar energy alone is insufficient to power the machine. The PV/T refrigerant branch is typically linked in a parallel configuration with an air-source heat exchanger. The evaporation capacity of each heat exchanger (HX), and therefore the proportion of refrigerant flowing through each branch of the circuit, is determined by the temperatures of the evaporators, the ambient temperature, and the heat gain. During periods of large solar energy, a greater proportion of refrigerant vaporizes on the PV/T side. Conversely, when the environmental temperature (from air or ground source) is higher, the evaporation capacity of the second source increases. Several authors conducted an experimental study on bypassing the solar circuit and condensing in the air-source heat exchanger for water cooling on the user side.

Wang et al. [78] performed a study on an innovative solar PV/T-air dual heat source heat pump system. The researchers created a new solar PV/T-air dual heat source composite heat pump system and constructed an experimental setup to study its immediate performance. The system comprised a composite heat pump with multiple heat sources, solar PV/T, and cooling systems. The experimental findings demonstrated that the solar PV/T collecting circulation achieved a maximum instantaneous producing efficiency of 15.0 %, with an average heat collecting efficiency of 43.8 %. These results were obtained under average ambient temperature and solar irradiation conditions of 6.5 °C and 581.5 W/m2, respectively. The average heat distribution ratio during operation was 28.1 % from solar energy, 35.7 % from air, and 36.2 % from the compressor. The heat pump exhibited an instantaneous coefficient of performance (COP) that varied between 2.0 and 2.6, with an average value of 2.5, which suggests excellent system performance.

In the new work Wang and colleagues [79] examined the energy and exergy components of a new dual-source heat pump system that includes integrated phase change energy storage. The system was created to overcome the drawbacks of conventional air source heat pumps in cold areas. It consists of a heat pump, photovoltaic-thermal modules, an air heat exchanger, and phase-change energy storage equipment. The heat pump may extract heat from various sources such as PV/T, ambient air, or the solidification latent heat of water in an ice tank, according to different external circumstances. The main innovation is the integration of phase-change energy storage in the ASHP system, which allows for indirect solar energy consumption via the ice tank and improves efficiency by supporting the air source. The study presents a new form of heat pipe phase-change thermal storage device (PCTSD) for building heating systems, providing a sustainable energy source for residential structures in cold areas. The results show a winter solar energy utilization ratio of 2/3 and an energy-saving rate of 73.6 % compared to standard ASHP systems, leading to a 69 % decrease in carbon emissions. The findings provide important technical knowledge for installing the innovative system in residential structures located in cold locations, showing significant enhancements in energy efficiency and reductions in

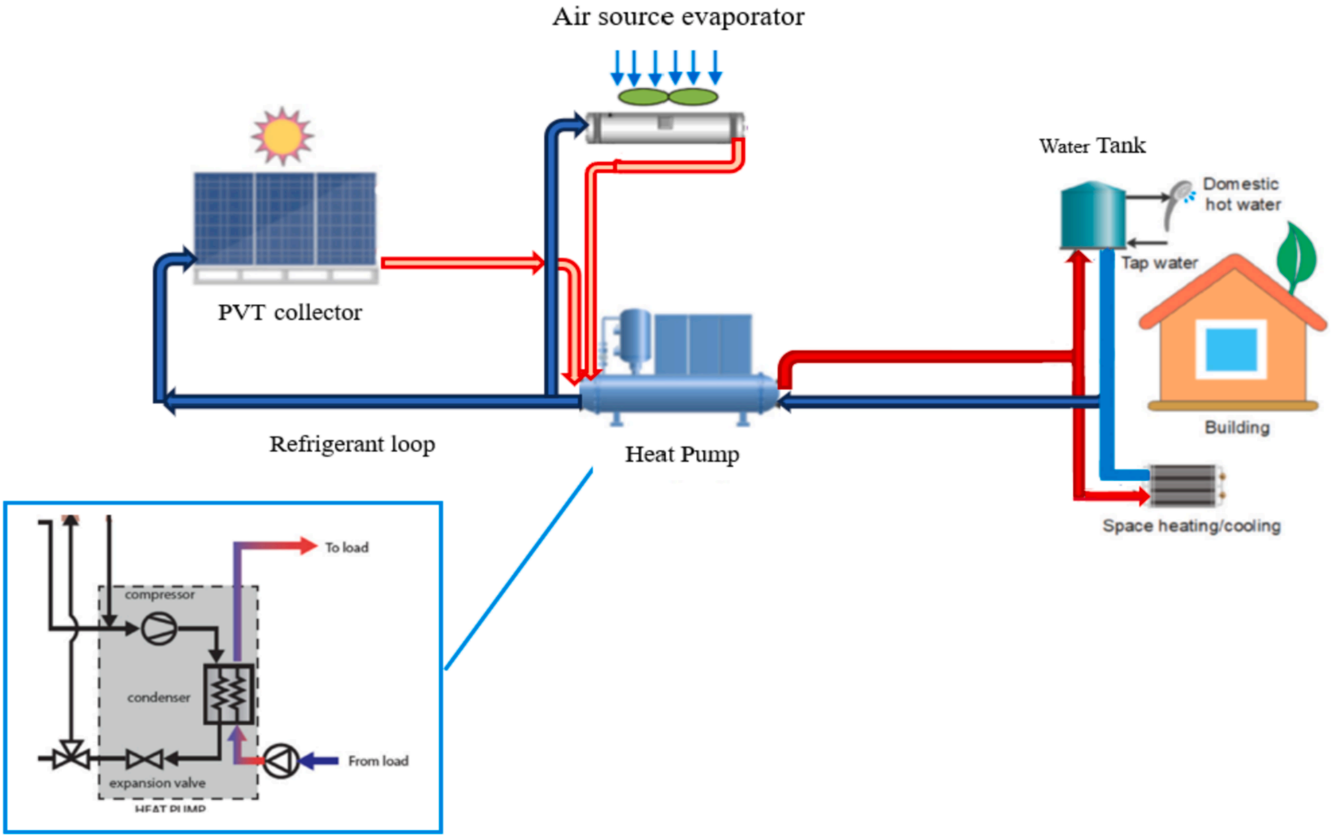

Fig. 6. General scheme of dual-source DX-PV/T-SAHP.

carbon footprint.

Cai et al. [80] conduct an analysis and optimization study that specifically examines the performance of a new type of heat pump water heater. This water heater utilizes a solar-air dual series source (SA-HPWH). Their proposition presents a concise design with clear-cut regulation, with the goal of improving system efficiency. They use dynamic modeling to assess the several elements that affect the operating features of the SA-HPWH system. Significantly, they note that when the water temperature increases, there is a reduction in the amount of heat produced by the evaporator on the air side. However, both the airside and collector evaporators see an increase in heat production, resulting in improved performance. In addition, it has been discovered that raising solar irradiation increases the heat output of the collector evaporator, while simultaneously reducing the heat output of the air-side evaporator, so improving the overall performance of the system. In summary, the research indicates that combining the SA-HPWH system with PV/T and conventional solar collectors as evaporators enhances performance in various operational scenarios, despite the evaporators having a comparatively lower heat gain.

Li and Huang [81] conducted a simulation analysis to assess the operational efficiency of a hybrid solar/air dual source assisted heat pump (S-A-AHP) water heater. The water heater runs in three modes: solar-air, solar, and air. Their research examined the system's performance under different solar radiation and ambient temperature settings, with a specific focus on identifying the most optimal mode switching technique and energy conversion efficiency. The findings indicate that using the mass flow ratio of the refrigerating medium as a basis for mode switching is more suitable than just depending on external conditions. The threshold ratio for switching from solar-air to solar mode is around 0.75. In addition, in conditions of minimal environmental advantages, with an ambient temperature of 0 ℃ and solar radiation intensity of 100 W/m2, the average coefficient of performance (COP) of the S-A-AHP is 29.7 % and 19.9 % greater than that of the conventional solar-assisted heat pump (SAHP) and air source heat pump (ASHP) respectively.

Cai et al. [82] introduced a new PV/T-air dual source heat pump water heater system (PV/T-AHPWH) that was analyzed using dynamic simulation and performance assessment. The study examines the PV/T-AHPWH system, which consists of a PV/T evaporator and an air source evaporator operating in parallel to concurrently capture energy from solar and ambient sources. A predictive model is created to analyze the behavior of the system, taking into account variables such as ambient temperature, solar radiation, and packing density. The findings suggest that higher solar irradiation levels amplify the heat absorption of the PV/T evaporator, while simultaneously diminishing the evaporating capacity of the air source evaporator. This has an impact on the distribution of mass flow and overall efficiency. In addition, the study investigates how ambient temperature and packing factor affect the performance of the PV/T-AHPWH system. It concludes that this system works better than a dual-source heat pump system that uses a regular solar thermal collector, demonstrating superior energy efficiency.

Fu et al. [83] conducted additional research where they utilized a novel photovoltaic heat-pipe collector in conjunction with an air-cooled heat exchanger, operating in parallel. This allowed them to optimize the heat source based on prevailing weather conditions. Furthermore, the production of domestic hot water (DHW) can be exclusively fulfilled by using PV/T/heat-pipes systems, provided that there is ample solar radiation available. Li and Sun [84] conducted an experimental test on a similar system, which involved a loop heat-pipe (LHP) PV/T combined with an air-source heat pump (HP) for water heating. The system was optimized using parametric TRNSYS simulations [103]. The concurrent operations of the two systems enable the provision of hot water under varying solar radiation conditions, including high, medium, or low levels. Typically, the direct combination of borehole heat exchangers (HX) with DX-PV/T-SAHP systems is not commonly done. However, there are instances where borehole HX have been used in conjunction with DX-PV/T-SAHP systems, such as the approach suggested by Yao et al. [43]. In their study, borehole HX was utilized on the user side to pre-heat water before it enters the machine. The system, which can function with either a single or dual power source, was simulated and analyzed using parametric simulations. These simulations revealed intriguing performance outcomes.

Yao et al. [85] investigated the enhancement of vapor-injection heat pump systems for residential heating in cold climates by incorporating PV/T collector/evaporators. Results indicate that the vapor injection (VI) cycle effectively mitigates the limitations of standard one-stage air source heat pump (ASHP) systems in severe cold. However, efficiency remains a challenge due to low evaporating temperatures in conventional fin-tube evaporators. In contrast, the PV/T collector/evaporator structure allows for higher evaporation temperatures, improving system COP. Their proposed system operates in three modes: one-stage with solar assistance, two-stage with solar assistance, and parallel ASHP with two-stage cycles. Comparative analysis reveals superior performance of the suggested system, achieving a COP of 4.42 at 0 °C ambient temperature and 500 W/m2 solar irradiation, compared to ASHP-VI and existing PV/T SAHP-VI systems, which attain COPs of 2.70 and 3.57, respectively. Notably, the proposed system excels particularly at low ratios of injected vapor mass flow rates.

Erdinc et al. [86] conducted research to investigate the possibility for improving performance by integrating a PV/T dual-source heat pump unit with a pressure booster ejector. It was discovered that both the dual-source heat pump and ejector independently enhanced the coefficient of performance (COP). Research on dual-source heat pumps generally examined collector efficiency, whereas studies on ejector heat pumps primarily did parametric analysis. The significance of regulating the temperature of the solar collector was underscored in order to optimize the advantages derived from the dual-source heat pump, ejector, and PV/T performance. The study utilized a setup in which the condenser exit is divided into two streams, therefore enhancing the efficiency of the system by regulating the evaporation pressures and mass flow rates. By conducting simulations under various weather situations, the ideal evaporation temperatures for the collector were identified, revealing a possible improvement in COP of 22.6 % under specified circumstances. By integrating power generated from the PV, a 5-kW heating supply has the potential to decrease grid electricity use by up to 75 % under identical circumstances.

Also, some authors do experimental research**.** Fang et al. [87] conducted experimental research on a DX-PV/T-SAHP system. This system was capable of supplying space heating (SH), space cooling (SC), and domestic hot water (DHW) in various operating modes, depending on the load and boundary conditions. The machine can generate domestic hot water (DHW) and space heating (SH) by harnessing energy from PV/T collectors or the surrounding environment. Additionally, it can provide space cooling (SC) by releasing energy into the DHW storage or the environment. A comprehensive mathematical model was utilized to conduct further analyses on the system's performances under various operating conditions [104].

Bae et al. [88] conducted a study to assess the effectiveness of a combined system that integrates photovoltaic-thermal (PV/T) technology with an air source heat pump (ASHP) for real-world uses. A full-scale experimental plant was built within a small office building to assess the effectiveness of the PV/T–ASHP system for heating and cooling. Their study entailed gathering extensive measurement data using a real-time monitoring system to accurately evaluate performance. Unlike previous research, their team developed and manufactured a dedicated PV/T module for the experiment, verifying its thermal and electrical effectiveness in real-world scenarios. An assessment was carried out to determine the appropriateness of the system by comparing it to previous research, including PV/T-ground source heat pump (GSHP) systems. The results showed that the PV/T–ASHP system had average coefficients of performance (COPs) for heating and cooling of 3.54 and 3.31, respectively. This is a 52 % improvement in COP compared to using only the ASHP. The PV/T–ASHP system showed a 9 % performance difference in comparison to PV/T–GSHP systems, while also having a 44 % lower starting cost. This indicates economic benefits and practicality in using PV/T–ASHP systems as an alternative to PV/T–GSHP systems for attaining Zero Energy Buildings (ZEB) in both existing and small-scale structures.

Zhang et al. [89] conducted an experiment to analyze the electrical and thermal efficiency of a large-scale photovoltaic solar-thermal dual-source direct expansion heat pump system. A novel direct-expansion PV/T heat pump system, DX-PV/T-HP, was created and tested in Hefei, a city renowned for its drastic seasonal temperature variations. The system used a plate-tube PV/T evaporator to produce electricity, space heating, and domestic hot water at the same time. An experiment was carried out to evaluate the heating efficiency and durability of a system with four operational modes: air-source heating, photovoltaic/thermal heating, heat storage heating, and defrosting/snowmelt, in the presence of extended copper piping. Performance indicators such as COP, power consumption, and condensing powers were evaluated in a three-day winter experiment. Photoelectric conversion efficiency and PV panel temperature were monitored simultaneously to assess the improvement in power performance. The plate-tube evaporator increased the photoelectric conversion efficiency of the solar panel by 25.0 % compared to conventional solar panels. The system had an average Coefficient of Performance (COP) of 4.96 when boiling water and generated more electricity than it used. The concept of comparable net thermal energy was proposed to effectively evaluate the system's performance, showcasing its ability to meet the basic living needs of rural residents.

Du et al. [90] conducted an experimental study on a photovoltaic/thermal-air dual heat source direct-expansion heat pump (DHS-DXHP) aimed at efficient and reliable heating and cooling alongside PV power generation. The design incorporated a novel PV/T air evaporator (PV/TAE) with micro heat pipe arrays (MHPAs) as the primary heat transfer element. These MHPAs, positioned at the back of PV modules, effectively cooled the surface, reducing module temperature by 31.6 °C and maintaining a minimal temperature difference of 2.1 °C along the module length. This resulted in a 5.3 % increase in photovoltaic efficiency. The system demonstrated an average heat collection efficiency of 106.1 % and COP values for heating in solar (S), combined solar and air (SA), and air (A) modes of 2.8, 2.1, and 2 respectively under winter conditions. In summer, the COP for cooling was 2.2, with PV system efficiency at 11.2 %.

Du et al. [91] conducted a Simulation study of a photovoltaic/thermal-air dual heat source direct-expansion heat pump, based on their prior research [90]. Their innovation consisted of developing a unique Photovoltaic/Thermoacoustic Energy (PV/TAE) system that utilized Metal Hydride Pair Assemblies (MHPAs) and finned air ducts. This system aimed to optimize renewable energy efficiency by capturing solar and air energy concurrently. By integrating PV/TAE with a heat pump system, researchers developed and verified simulation software to assess the effects of solar irradiance and ambient temperature on both thermal and electrical efficiency in two operational modes. The results showed that the average COPh values varied between 1.42 and 3.44 in solar/air mode and between 1.44 and 3.42 in solar mode, confirming the successful use of both heat sources. They developed an operational plan in which the system changes modes depending on the amount of solar radiation. Exergy analysis identified potential for improvement, namely by improving the heat transfer zones in the evaporator and compressor.

4. Discussion

The Direct Expansion Solar Assisted Heat Pump (DX-SAHP) system is a distinct form of solar-assisted heat pump that integrates solar collectors and heat pumps directly, without the need for an intermediate fluid. Research conducted by Song [54], Chen [50], Liu [70], has examined the efficacy and practicality of DX-SAHP (Direct Expansion Solar Assisted Heat Pump) systems in various scenarios, emphasizing its capacity to offer efficient heating and cooling solutions. Moreover, researchers have investigated the combination of thermoelectric generators, heat pipes, and innovative control systems to improve the efficiency and stability of the system. Current research is focused on maximizing the efficiency of DX-SAHP systems to facilitate the shift towards sustainable energy solutions.

The DX-PV/T-SAHP system combines hybrid PV/T technology with heat pumps for water heating and has undergone extensive analysis to enhance efficiency and efficacy. Zhou [62], Ito [68], Ji [69], Liu [70], Yao [71], Zhang [72], and other researchers have concentrated their efforts on improving system performance through practical experimentation, computer modelling, and theoretical analysis. Utilizing PV/T collectors as condensers during overnight operation has demonstrated potential for practical use in enhancing refrigeration efficiency and preserving cold water for daytime utilization. Continuous innovation and optimization are crucial for achieving maximum energy efficiency and meeting the varied demands of residential and commercial applications. This advancement is necessary to provide sustainable heating and cooling systems.

The data shown in Table 2 provides detailed information on the performance metrics of several DX-PV/T-SAHP systems. Initially, the coefficient of performance (COP) showed considerable variation among the investigations, with values ranging from about 2.9 to 7.67. The variation can be ascribed to disparities in system setups, operational circumstances, and geographical locations. The COP values are determined by factors such as solar irradiation, condenser water temperature, and flow rate. Generally, more sun irradiation results in better electrical performance. Furthermore, the electrical efficiency of the systems, which indicates the proportion of solar energy that is transformed into electrical energy, varied between about 13.1 % and 16.87 %. The thermal efficiency, which is the proportion of solar energy turned into thermal energy, ranged from around 55.0 % to 60.12 %. The overall energy efficiency, which takes into account both electrical and thermal efficiencies, varied between about 69.1 % and 74.20 %. Furthermore, variations in yearly energy production were noted, with electrical energy ranging from 303.51 kWh to 1364 kWh and thermal energy ranging from 810 kWh to 3213.12 kWh. The variances highlight the different performance characteristics of direct expansion solar-assisted heat pump systems and emphasize the significance of design factors and operating circumstances in getting the best performance.

However, the dual-source DX-PV/T-SAHP system is an innovative approach to enhance the utilization of solar energy and optimize overall system efficiency, particularly under demanding operating conditions. By including an additional heat source, often air, onto PV/T collectors, these systems may operate with greater reliability and efficiency, ensuring continuous operation even when solar energy alone is insufficient. Multiple studies, conducted by Wang [78], Cai [82], Li [81], Fu [83], Yao [85], among others, have examined different aspects of dual-source DX-PV/T-SAHP systems. These aspects include system design, performance evaluation, mode switching techniques, and energy conversion efficiency. These studies have demonstrated that these systems possess the capacity to achieve elevated levels of efficiency and performance in many operational scenarios, leading to significant energy conservation and reductions in carbon emissions, particularly in cold regions. Moreover, the practical functionality of dual-source DX-PV/T-SAHP systems has been extensively studied by Fang [87], Bae [88], Zhang [89], Du [90], and other researchers, leading to valuable empirical insights.

These studies have confirmed the effectiveness of these systems in providing heating, cooling, and hot water production for buildings. They have also highlighted the versatility and practicality of these systems, particularly in achieving Zero Energy Buildings (ZEB) and meeting the diverse energy needs of residential and small-scale commercial buildings. Furthermore, Du and other researchers have carried out simulation experiments that have improved the optimization of dual-source DX-PV/T-SAHP systems. They accomplished this by developing and verifying

Table 2
A summary of the key numerical findings from each paper concerning single source.

Ref.	Parameters	Results
Chen et al. [50]	COPth and COPPV/T vs. solar radiation	Increase by 0.05 and 0.12 per 100 W increase in solar radiation
	Heat output power and electrical output power vs. solar radiation.	Both increases, but thermal, electrical, overall energy, and exergy efficiency decrease with increasing solar radiation
	COPth and COPPV/T vs. ambient temperature	COPth increases by 0.08 and COPPV/T decreases by 0.09 per 5 °C increase
	Heat output power and thermal efficiency vs. ambient temperature	Both increases, while electrical output power, electrical efficiency, and exergy efficiency decrease with increasing ambient temperature
	COPth and COPPV/T vs. supply water temp in condenser	Decrease by 0.25 and 0.35 per 5 °C increase
	COPth and COPPV/T vs. packing factor	COPth decreases by 0.017 and COPPV/T increases by 0.26 per 0.15 increase in packing factor
	COPth and COPPV/T vs. heat pipe pitch	Both decrease by 0.02 and 0.04 per 5 mm (about 0.2 in) increase
	COPth and COPPV/T vs. PV backboard absorptivity	COPth increases by 0.03 and COPPV/T decreases by 0.03 per 0.15 increase in PV backboard absorptivity
Zhou et al. [62]	Average electrical power, vs. Average electrical efficiency	286 W, 11.8 %
	Daily cumulative power generation on sunny days vs. Daily cumulative power generation on overcast days	2 kWh, 1.5 kWh
	Average heating power	4.7 kW
	Average unit thermal efficiency	120 %
	Average system heating COP	6.16
Jian Yao et al. [51]	Average electrical efficiency	17.93 %
	Average thermal efficiency	109.4 %
	Average system COP	5.43
	CO2 emissions reduction compared to traditional supply	565.8 kgCO2
Liu et al. [70]	PV/T system performance vs. A/Vth	Higher COP and adaptability with larger A/Vth, thermal performance declines with increasing A/Vth
	Effect of solar irradiation and ambient temperature on A/Vth	Strengthens positive effect on thermodynamics performance, weakens negative effect on heat collection performance
	Optimized A/Vth range	1.535 to 1.919 m^2h/m^3
Mi et al. [65]	Performance during daytime stage operation	COP 2.95; heats 1.1 tons of water from 10 °C to 50 °C in 99 min
	Performance during nighttime stage operation	COP 2.55; heats water in 124 min at −0.1 °C ambient temperature
	Performance during continuous operation	COP 2.07; maintains water temperature close to 50 °C
	Regional applicability (average COP of continuous vs. improved operation)	Severe cold zone: 1.74 vs. 2.41; Cold zone: 2.00 vs. 2.76; Hot summer and cold winter zone: 2.10 vs. 2.88
	Stage operation vs. continuous operation COP difference	Stage operation COP is 42 % higher than continuous operation on average
Yao et al. [71]	Efficiency factor vs. evaporator unit type	Hexagon: 0.521, Grid: 0.564, Rectangle: 0.549, Linear: 0.342 (at 10 mm fluid channel width)
	Temperature distribution uniformity vs. evaporator unit type	Hexagon and Rectangle: better uniformity but higher-pressure loss; Grid and Linear: opposite
	PV cells' temperature reduction vs. evaporator unit type	Grid: 23.4 °C (600 W/m^2 solar radiation), electrical efficiency improvement: 12.2 %

(continued on next page)

Table 2 (*continued*)

Ref.	Parameters	Results
	Recommended fluid channel width and scaling ratio	8 mm to 13 mm; scaling ratio: 0.8 to 1.2
	Combined evaporator unit types recommendation	PV/T collector/evaporator: Hexagon and Grid, or Rectangle and Grid; Direct expansion evaporator: Grid and Linear, or whole Grid
Chen et al. [77]	COP vs. radiation	COP ranged from 2.9 to 4.6 (200 W/m^2 to 800 W/m^2)
	COP vs. water temp	COP dropped from 5.2 to 3.2 (25 °C to 45 °C)
	COP vs. water flow	COP dropped from 6.7 to 2.8 (1 L/min to 5 L/min)
	Electrical efficiency vs. radiation	Improved by up to 1.9 % with increasing radiation
	Electrical efficiency vs. water temp	Little effect
	Electrical efficiency vs. water flow	Little effect
Zhou et al. [55]	Experimental elec. Efficiency vs. Simulated elec. efficiency	13.1 %, 13.7 %
	Experimental thermal efficiency vs. Simulated thermal efficiency	56.6 %, 55.0 %
	Experimental overall energy efficiency vs. Simulated overall energy efficiency	69.7 %, 69.1 %
	Experimental COP vs. Simulated COP	4.7, 5.0
	Simulation error	Maximum error: 7.2 %
Rabelo et al. [66]	Economic optimum collector size	Same for any solar radiation and ambient temperature; affected by wind speed with payback variation around 0.8 % (0–9 m/s)
	COP vs. collector area and radiation	COP almost proportional to collector area and solar radiation
	Compressor performance	Lower displacement compressor has higher COP, lower payback time, and lower optimum collector size
	R134a vs. R290	R290 has 25 % higher COP but 19 % higher payback time
	Sensitivity analysis	Payback time strongly affected by electricity and fixed costs; optimum collector size strongly affected by collector and fixed costs
	Case study (Belo Horizonte, Natal, Florianópolis)	Payback times: 1.77, 2.06, and 3.24 years respectively; similar to Singapore
	DX-SAHP vs. ASHP and IXSAHP	DX-SAHP for Belo Horizonte has lower payback
Mohanraj et al. [63]	ANN performance	Correlation coefficient of 0.999 with minimum RMS and COV values
	ANN application	Successful prediction of DXSAHP performance at different solar intensities and ambient temperatures
Liu et al. [67]	Total annual thermal production	1071.67 GJ
	Net electricity consumption	20.30 GJ
	Annual COPo	6.43
	Enhancement of annual electricity output	9.67 %
Song et al. [54]	COPPV/T at 800 W/m^2, 10 °C ambient temp, 30 °C water temp	7.67 (FPV/TEG), 7.35 (FPV), 5.85 (PV)
	Total efficiency at 300 W/m^2, 10 °C ambient temp, 30 °C water temp	226.84 % (FPV/TEG), 226.02 % (FPV), 191.65 % (PV)
	Exergy efficiency at 700 W/m^2, 10 °C ambient temp, 30 °C water temp	30.55 % (FPV), 29.18 % (FPV/TEG), 19.85 % (PV)
	Optimal COPPV/T	9.17 (10 °C ambient temp, 22 °C water temp, 800 W/m^2 irradiation)
	Optimal total efficiency	250.61 % (16 °C ambient temp, 22 °C water temp, 300 W/m^2 irradiation)
	Optimal exergy efficiency	30.52 % (10 °C ambient temp, 30 °C water temp, 800 W/m^2 irradiation)
Abbas et al. [52]	Electrical efficiency	Maximum instantaneous average: 14.08 %
	Thermal efficiency	Maximum instantaneous average: 66.71 %
	Electrical gain	Increased from 76 W to 86 W under solar irradiation of 500–760 W/m^2
	System size	163 m^2, generating 0.86 kW/day electricity and 6.35 kW/day thermal energy
	COP	Average: 6.11, Maximum: 7.1
	Model validation	Numerical findings in strong agreement with actual data (max relative error: 5.16 %)
Han et al. [64]	Superheat stability (max overshoot)	3.2 °C (cloudy skies), stabilization time: 20–42 min
	Household mode performance	Heating power: 16.69 kW, Compressor power: 4.74 kW, COP: 3.51, PCE: 13.25 %, CHE: 34.92 %
	Commercial mode performance	Heating power: 16.72 kW, Compressor power: 5.18 kW, COP: 3.16, PCE: 13.78 %, CHE: 32.83 %
Abbas et al. [53]	Electrical efficiency	Mean daily: 14.08 %
	Thermal efficiency	Mean daily: 60.12 %
	Overall energy efficiency	Mean daily: 74.20 %
	Exergy efficiency	Mean daily: 18.12 %
	Annual electrical energy generation	303.51 kWh
	Annual thermal energy generation	3213.12 kWh
	Average COP	6.7
Song et al. [61]	Electrical performance	Highest monthly electricity generation: 125 kWh in Garze, annual power generation: 1364 kWh in Garze (vs. 85 kWh monthly, 810 kWh annually in Hefei)
	Electrical efficiency	Highest: 16.87 % in Garze, lowest: 16.19 % in Hong Kong
	TEG generation	Highest: 5.7 kWh annually in Hong Kong
	Heating capacity	Highest: 12,180 kWh annually in Hong Kong
	COP and NEER	Highest: 5.1 (COP), 8.0 (NEER) in Garze
	Exergy efficiency	Highest annual average: 23.08 % in Garze
	Economic and environmental benefits	Heat pump system saves 2/3–3/4 energy and heating costs, reduces 1/2–2/3 carbon emissions compared to traditional gas boiler

simulation software that assesses the system's performance under different environmental conditions. These studies have identified certain areas for enhancement, such as enhancing the heat transfer zones in the evaporator and compressor, to further enhance the efficiency and reliability of the system.

The research conducted on dual-source DX-PV/T-SAHP systems emphasizes its capacity to serve as sustainable and efficient solutions for water heating, space heating, and cooling applications. These systems provide substantial advantages in terms of energy efficiency, environmental sustainability, and operational dependability. Continual research and development in this field are vital for improving the effectiveness of these systems and expediting their integration into the transition towards more eco-friendly energy systems.

The research summarized in Table 3 for dual-source DX-PV/T-SAHP investigates several approaches to improve the performance of heat pump systems, with a specific focus on residential and small-scale office buildings. An effective strategy entails incorporating solar and air sources into the system design. For instance, a vapor-injection heat pump system equipped with a PV/T collector/evaporator demonstrated better efficiency in cold regions when compared to traditional ASHPs and current PV/T systems. Similarly, a heat pump that is aided by two energy sources combines a PV/T collector/evaporator with an air-cooled evaporator. This allows for the efficient use of both solar and air energy, resulting in a high coefficient of performance (COP) and power output.

New research introduced a unique PV/T-air dual source heat pump water heater (PV/TAHPWH) that combines PV/T and air source evaporators to generate both hot water and power. The performance of this system increased with more solar irradiation, compensating for any inefficiencies under unfavorable conditions. Moreover, a PV/T-ASHP system exhibited improved heating and cooling efficiency in a small office building, courtesy of the PV/T module that reduced a substantial amount of the system's power usage. Additional investigation examined the operational attributes of solar-air dual series source heat pump water heaters (SA-HPWH) and PV/T air dual heat source direct-expansion heat pump systems. The findings indicated enhanced performance when solar radiation and air velocity increased, especially in winter.

Another novel method involves the utilization of a solar heat source-assisted heat pump unit that incorporates an ejector, resulting in enhanced system efficiency through the utilization of solar heat input, as opposed to traditional systems. Moreover, a PV/T-air dual heat source composite heat pump system efficiently harnessed waste heat produced by PV cells, leading to a high coefficient of performance (COP) and energy utilization. Finally, there are large-scale direct expansion PV/T heat pump systems available for rural communities that combine photovoltaic and solar-thermal aided heat pump technologies. These systems have been shown to operate reliably and provide excess electricity when solar radiation conditions are favorable. These studies offer useful insights into improving the energy efficiency and overall performance of heat pump systems by combining solar and air sources, using dual-source systems, and using innovative technology such as PV/T collectors and ejectors.

Table 3
Summary of the key numerical findings from each review paper concerning dual-source.

Paper	Parameters	Results
Yao et al. [85]	COP comparison at 0 °C, 500 W/m^2	Proposed system: 4.42, ASHP VI: 2.70, PV/T SAHP VI: 3.57
	System operation	Self-operation at solar radiation >400 W/m^2
	COP at −10 °C, 400 W/m^2	COP: 3.42, Electrical efficiency: 15.2 %, Thermal efficiency: 43.8 %, Overall efficiency: 83.9 %
	Maximum COP	COP: 4.30 at mass flow ratio 5 %, solar irradiation 500 W/m^2, ambient temperature −10 °C
	Levelized cost of heat	Proposed system: 0.054/kWh (44.7 % lower than ASHP VI, 48.5 % lower than gas water heater, 51.5 % lower than electric water heater)
Li et al. [81]	Mode switching criterion	Mass flow ratio γ critical value: 0.75
	Performance at 10 °C, 400 W/m^2	Heating power: 1585 W, Generating power: 162 W, COP: 4.76, Electrical efficiency: 13.5 %
	Stability in unfavorable environment	Better heating capacity and COP than conventional system
	High-latitude performance	Higher heating capacity and COP with smaller PV/T collector area
Cai et al. [82]	COP with rising solar irradiation	COP increases from 2.25 to 2.66 (100 W/m^2 to 300 W/m^2)
	COP with rising ambient temperature	COP increases by 18.22 % (10 °C to 30 °C)
	Mass flow distribution with solar irradiation	Increases from 21.13 % to 47.23 % (100 W/m^2 to 300 W/m^2)
	Packing factor impact	Higher packing factor increases electrical efficiency and COP
	Mass flow distribution with ambient temperature	Decreases from 21.69 % to 13.79 % (10 °C to 30 °C)
Bae et al. [88]	Thermal and electrical efficiencies	Thermal: 18.9 %, Electrical: 10.9 %
	Average COPs	Heating: 3.54, Cooling: 3.31
	Performance improvement	Up to 52 % better than ASHP
	Power offset	18 % in winter, 27 % in summer
	Economic benefits	44 % lower initial investment cost compared to PV/T-GSHP
Cai et al. [80]	COP with solar irradiation	COP increases from 2.23 to 2.40 (100 W/m^2 to 500 W/m^2)
	COP with ambient temperature	COP increases from 2.23 to 2.63 (10 °C to 20 °C
	Impact of air velocity	COP increases with air velocity up to 3 m/s
	Comparison with normal solar collector	PV/T collector improves overall performance under various conditions
Du et al. [90]	PV cooling effect	| Temperature decrease: 31.6 °C, PV efficiency increase: 5.3 %
	Average PV efficiency	12.8 %
	COP under typical heating conditions	S mode: 2.8, SA mode: 2.1, A mode: 2.0
	COP under typical cooling conditions	2.2
	Seasonal performance	S mode thermal performance 18.2 % higher than A mode
Du et al. [91]	Simulation model reliability	Relative errors within 10 % between simulation and experimental values
	COPh in SA mode	1.42–3.44
	COPh in S mode	1.44–3.42
	COPh vs. ambient temperature	COPh increased with ambient temperature
	COPh vs. irradiation	COPh less affected by ambient temperature as irradiation increased
	Exergy efficiency	SA mode: 4.37 %, S mode: 4.41 %
	Exergy loss components	PV/TAE and compressor accounted for 61.9 % to 83.9 %
Erdinc et al. [86]	COP improvement	Improved by 22.6 % with solar input and ejector
	Electricity reduction from grid	Reduced by 75 % with 15 m^2 PV/T collector

(*continued on next page*)

5. Conclusions and future perspectives

The present paper discusses advancements and research in Direct Expansion Solar-Assisted Heat Pump (DX-SAHP) systems and their integration with photovoltaic (PV) and photovoltaic-thermal (PV/T) technologies to improve heating efficiency. In the scientific literature, many aspects have been deepen, such as:

the effects of integrating thermoelectric generators (TEG) into PV systems, showing enhanced performance metrics;

the effectiveness of a heat-pipe solar PV/T heat pump system, showcasing increased efficiency with more solar radiation and optimized design parameters.

the cogeneration efficiency of roll-bond-PV/T heat pump systems, demonstrating substantial promise for real-world application.

In some papers, artificial neural networks have been used for system optimization. Moreover, economic studies highlighted the viability and benefits of DX-SAHP systems, focusing on proper sizing and environmental factors. To sum up, all papers agree that hybrid PV/T and solar thermal systems show better performance compared to traditional systems [49]. These investigations enhance the comprehension and improvement of DX-SAHP systems, facilitating their extensive use in sustainable heating applications.

The DX-PV/T-SAHP system is a cutting-edge method of using hybrid

Table 3 (*continued*)

Paper	Parameters	Results
Wang et al. [78]	Electric gain and heat-collecting capacity	25.0 W to 239.0 W (electric), 235.2 W to 844.2 W (heat-collecting)
	Photoelectric efficiency	12.7 %
	Heat-collecting efficiency	43.8 %
	COP of heat pump system	2.0 to 2.6 (mean: 2.5)
Zhang et al. [89]	PV generated power (sunny/cloudy days)	22.5 kWh (sunny), 15.75 kWh (cloudy)
	Photoelectric conversion efficiency	15.71 % with heat pump, 11.1 % increase
	COP under different conditions	8.6 to 4.2 (Jan 13), 9.3 to 3.7 (Jan 14), 8.8 to 3.4 (Jan 15)
	COP improvement over air-source HP	4.0 % to 22.4 %
Wang et al. [79]	COP in different modes	I mode: 2.6, S mode: 3, A mode: 2.4
	Solar energy utilization	Heat collection power of PV/T: 7.8 kW (500 W/m^2)
	Power consumption reduction	Reduced by 26.4 % compared to traditional ASHP
	Energy-saving rate	73.6 %
	Investment payback period	6.1 years
	Carbon emission reduction	69 %

PV/T technology for water heating purposes, displaying encouraging outcomes under different climatic situations. In the scientific literature, attention has been paid to numerical simulation models for DX-PV/T-SAHP systems with microchannel PV/T evaporators, showing satisfactory electrical, thermal, and overall energy efficiencies. Also a refined hybrid collector for DX-PV/T-SAHP systems has led to an increased coefficient of performance (COP) by minimizing pressure losses and enhancing the distribution of refrigerant inside the PV/T. An analysis of the influence of PV/T module area on system efficiency has shown appropriate A/Vth ratios for enhanced coefficient of performance (COP), especially in colder climates.

Studies on the effectiveness of two-phase flow channel designs in PV/T evaporators have suggested the use of a hexagon-grid connected fluid channel unit to improve thermal and electrical performance. The development of a revolutionary PV/loop-heat-pipe system for domestic hot water production has successfully attained high COP values and effectively shown the benefits of combining it with a heat pump. The integration of a ventilated microchannel PV/T façade system with a direct-expansion system has shown exceptional real-world efficiency in generating hot water. The use of a real-time integrated control approach for DX-PV/T-SAHP systems, which optimizes compressor frequency according to current radiation levels, has resulted in substantial improvements in energy efficiency. An empirical investigation of the energy efficiency of a PV/T + HP system in Nottingham, England, has shown that higher radiation levels lead to enhanced COP and has offered valuable insights into the system's performance under different operating situations.

Investigating novel arrangements in which PV/T collectors operate as condensers at nighttime, either by storing cold water for day use or reducing the temperature of cold storage facilities, has shown potential uses beyond conventional water heating.

Ultimately, the dual-source DX-PV/T-SAHP system provides a novel method for optimizing the consumption of solar energy and improving the efficiency of the system. This is achieved by including a secondary heat source, often air, in conjunction with PV/T collectors. This combination enables enhanced performance, especially under adverse operating situations when solar energy alone may not be enough. Multiple studies have shown that these systems are more successful than traditional systems in obtaining better coefficients of performance (COPs) and energy efficiency, especially in cold areas. Furthermore, studies have emphasized the need of using dynamic modeling, system optimization, and new designs to further improve the efficiency and dependability of dual-source heat pump systems. Dual-source DX-PV/T-SAHP systems provide great potential for providing sustainable heating, cooling, and hot water production in both residential and commercial buildings. These systems can help save energy and decrease carbon emissions.

CRediT authorship contribution statement

Hamed Namdar: Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Eugenia Rossi di Schio:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Conceptualization. **Giovanni Semprini:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Conceptualization. **Paolo Valdiserri:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Conceptualization.

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.

Data availability

No data was used for the research described in the article.

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