



## A comprehensive review of the hybrid heating systems consisting of heat pumps and solar collectors for hot water and space heating application



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### HIGHLIGHTS

- A survey on DX-SAHP and ID-SAHP performance was conducted.
- DX-SAHP performance varies greatly across regions.
- Evaporators are added to boost DX-SAHP when sunlight is low.
- Parallel IDX-SAHP excels in summer and transition seasons.
- Comparative study of IDX-SAHP configurations presented.

### ABSTRACT

A solar-assisted heat pump system is a hybrid system that integrates a solar collector and a heat pump, serving diverse functions such as space conditioning, drying, and generating heated water. The system's classification is based on the connection configuration of the solar collector and heat pump, which may involve a serial, parallel, or dual arrangement. Solar-assisted heat pump systems enhance output efficiency by harnessing solar energy in various heating modes, with the effectiveness contingent on the prevailing environmental conditions. As stated above, these systems are essential in lowering power consumption and reducing emissions. This study comprehensively assesses the research and development of solar-assisted heat pumps for building applications. This study delves into the classification of these systems, including direct expansion and indirect expansion solar-assisted heat pumps. Each configuration is to be detailed, and their thermal performance and demonstration samples are thoroughly examined. Furthermore, the study includes the assessment of energetic indicators for individual components and the overall system. Additionally, an investigation has been conducted on various refrigerant types that show promising potential for use in solar-assisted heat pump systems. It shows that adding an air evaporator to direct expansion solar-assisted heat pump solves the systems' deterioration during the absence of solar energy. The effect of climate on the indirect solar-assisted heat pump can be solved by designing the system to work in parallel or series configuration, depending on the solar energy availability.

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### 1. Introduction

Buildings consume more energy than the combined energy consumption of the industrial and transportation sectors, especially in developed countries [1,2]. Currently, facilities consume thirty percent of the globally consumed energy [3,4], and devices that provide conditioning and heating contribute to around 40% of this consumption [5]. In recent years, fossil fuel prices have risen rapidly, increasing space heating costs [6]. Subsequently, developing an energy production technology for buildings that is both sustainable and cost-effective is a challenge on a worldwide scale. Enhancing construction techniques, optimizing energy efficiency, and implementing strategies to reduce energy demand in buildings can effectively reduce emissions from facilities. This can be achieved by controlling emissions directly from the energy source or decreasing overall energy consumption. Solar energy is abundant and easily accessible, and studies have shown that it has a higher production efficiency than other forms of energy [7,8].

Consequently, solar energy usage will gain widespread acceptance. It could be used as a significant auxiliary energy source, especially in regions with enough solar radiation [9]. The heat pump has been employed in numerous investigations of hybrid systems. Using a heat pump for heating is more efficient than other methods, such as using a heater powered by electricity and burning [10]. One of the problems with solar power is that it is out of phase with the energy demand (SH and DHW). Combining

heat pump equipment with a solar collector could improve the system's overall effectiveness [11]. A SAHP system is a technique for minimizing the release of carbon dioxide (CO<sub>2</sub>) by decreasing or avoiding Traditional energy usage (coal, natural gas, etc.). The device can convert and transmit solar heating energy through absorbers, water, or operational media. Additionally, this system permits heat transfer for storage requirements [12]. Several studies on the fundamentals of system design, modeling, performance parameter optimization, and actual evaluations of prototype systems have been published in the literature [13]. Liu et al. [14] studied the performance and practicality of a solar air source heat pump (SASHP) heating system in Xining City, utilizing data from a low-energy residential building. Long et al. [15] presented a hybrid air source heat pump and solar hot water. Several connection approaches are offered, including SHW, ASHP, parallel mode, series mode, and preheating type connection method of solar hot water as air source heat pump's heat source. Kunelbayev et al. [16] studied the availability of the solar-heat supply system in a cold region of Kazakhstan with limited sun exposure. Some of the parameters studied in the numerical model investigations are shown in Table 1.

**Table 1:** Parameters of numerical studies

Parameters of the Study	Ref.
Solar collector: flat plate coll. 150 m <sup>2</sup> , Tilt 45°, water flow rate= 15,840 kg/h Storage tank: 105 m <sup>3</sup> , initial water temp.=15 °C Hot water storage tank volume =9.6 m <sup>3</sup> Water-to-water heat pump: 116.7 kW(FHP-WW360) Air-to-water heat pump: 136 kW (Tsinghua Tongfang-FS-L-R-120)	[17]
Solar collector: Evacuated collector, area= 860 m <sup>2</sup> , Tilt=59° Storage tank: 60 tons, initial water Temp.= 0 °C Heat pump: Two WSHP of 48 kW for serial system. Five ASHP of 19 kW for parallel system. Load: DHW	[18]
Solar collector: Flat plate collector, area = 150/140/230 m <sup>2</sup> , number in series 75/70/115. ASHP Rated heating capacity 80 kW. Rated input power 18 kW. Working fluid (R134a). Tank volume 10 m <sup>3</sup> . Climate: Collector tilt angle in Summer Mode, winter mode, and Climate: Changsha, Haikou (Latitude of 20.0°N) and Beijing (Latitude of 39.9°N). Collector tilt angle in Summer Mode (Latitude-10), in the Winter Mode (Latitude+10), and the Transition Mode (Latitude) Load: DHW	[19]

This study comprehensively reviews old and recent solar-assisted heat pump systems in building heating applications. This study includes the system's classification, which divided these systems into direct and indirect expansion solar-assisted heat pumps, and the development of each type of system. Also, this study presented a summarized definition of the TRNSYS software that is used commonly to solve these systems theoretically. TRNSYS components used in research in literature were listed.

## 2. Configurations of solar-assisted heat pump systems

The term SAHP, which is an abbreviation of solar-assisted heat pump, can be defined from its name as a combination of solar collectors and heat pumps to be a hybrid heating system. where the solar collector can be a flat plate solar collector (FPC) with or without a glass cover, an evacuated solar collector, or photovoltaic thermal collector PVT. The heat pump can also be an air or water source heat pump. The solar collector absorbs solar radiation and converts it to thermal power. The PV module, on the other hand, is the system's power source for the electrical devices [20]. The SAHP systems are classified into two variants: direct expansion SAHP systems (DX-SAHP) and indirect-expansion SAHP systems (IDX-SAHP) based on a variety of heat pumps and solar collector integration strategies [21]. Depending on how the heat pump and the solar collector are connected, the IDX-SAHP can be classified into series, parallel, or complicated. The solar collector is used in a series of connection to heat the heat pump's evaporator. In contrast, in a parallel connection, the heat pump and the solar collector are connected to the system to work separately and reject the heat in the storage tank. In a complicated system, the heat pump and the solar collector are connected so that the system can work either in a series or parallel mode or simultaneously with the two modes. In DX-SAHP, the heat pump can be designed with two evaporators ( solar evaporator and air evaporator). So, these two evaporators can be connected in series or parallel.

### 2.1 Direct-expansion solar-assisted heat pump (DX-SAHP) systems

The DX-SAHP are systems in which the solar thermal collector and heat pump evaporator are integrated into one unit. This integration keeps the cycle evaporator at a relatively high temperature, so the cycle COP improved significantly [22,23], as shown in Figure 1. The essential objective of DX-SAHPs is to ensure efficient and stable performance in various places. Additional research findings revealed that DX-SAHP performance in other areas varies significantly owing to the effect of sunlight since the refrigerant directly moves within the collector [24].

Numerous studies focused on assessing the influence of system components such as the collector-evaporator, expansion valve, condenser, and compressor on the system's overall performance. Most studies focused on collector evaporators looked at both types of flat plate solar collectors, the covered and uncovered collectors. Researchers employ these kinds of collectors for DX-SAHP, and this is widespread. The unglazed flat plate collector is undoubtedly the most widely used of the two types. This is attributed to its ability to achieve high collector efficiency, thereby promoting its widespread utilization. Since the thermal performance of DX-SAHP decreases when there is insufficient solar radiation, the air source evaporator can be added and

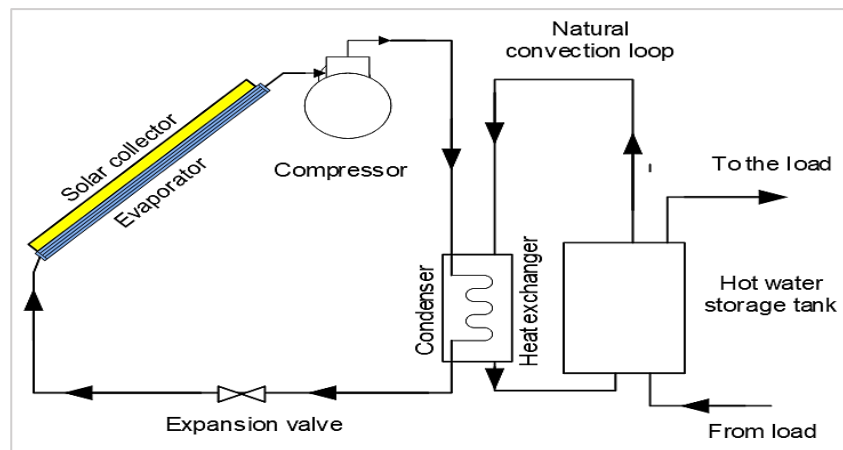
arranged in series connection with the solar collector evaporator, as shown in Figure 2a [25], or parallel connection with the solar collector evaporator, as shown in Figure 2b [26]. The comparison study by Cai et al. [25] on the air solar-solar assisted heat pump (AS-SAHP), DX-SAHP, and ASHP shows the effect of connecting the air source in series with the solar evaporator. This is illustrated in Table 2, which provides the values of power consumption. Table 3 presents the values of the coefficient of performance (COP). The study indicates that the DX-SAHP has the highest power usage, followed by the AS-SAHP system. In contrast, the ASHP system has the lowest power consumption. The COP of the AS-SAHP system was the highest, followed by DX-SAHP, while the COP of the ASHP system was the lowest.

**Table 2:** Power consumption of AS-SAHP, DX-SAHP, and ASHP systems

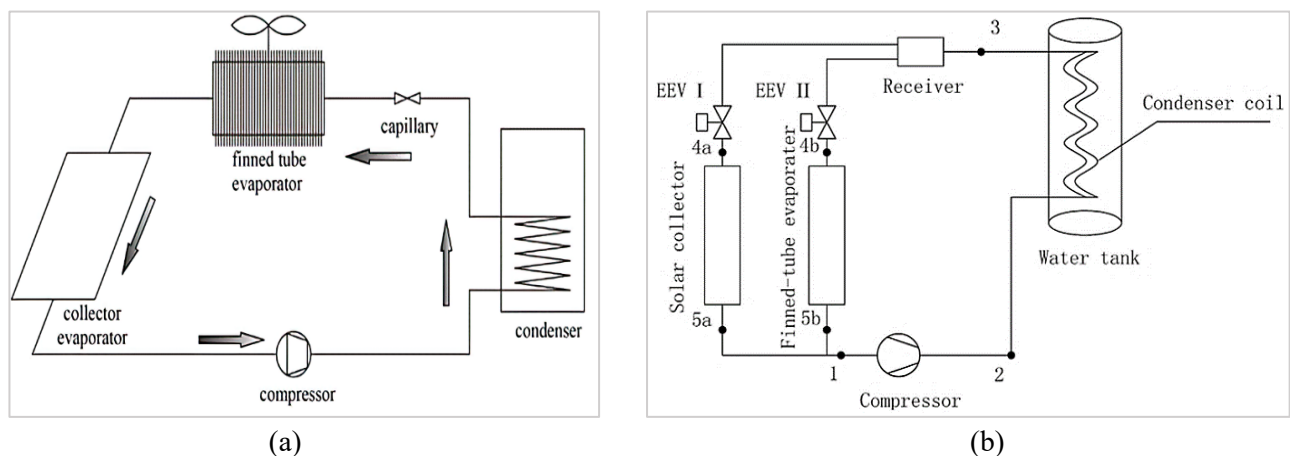
Ambient Temp.(°C)	Consumption of AS-SAHP (W)	Consumption of DX-SAHP (W)	Consumption of ASHP (W)
10	711.31	735.39	694.23
20	734.24	750.83	722.87
30	749.35	765.68	728.97

**Table 3:** COP of AS-SAHP, DX-SAHP, and ASHP systems

Ambient Temp.[°C]	COP of AS-SAHP	COP of DX-SAHP	COP of ASHP
10	3.15	3.03	2.70
20	3.50	3.34	3.14
30	3.69	3.50	3.47



**Figure 1:** Schematic diagram of DX-SAHP [24]



**Figure 2:** a) Series mode of modified direct-expansion solar-assisted heat pump and b) parallel mode of modified direct-expansion solar-assisted heat pump [27]

Krakow and Lin [28] conducted a study on a direct expansion SAHP system that used collector plates with fins for room heating. They argued that systems with glazed solar collectors are superior to those without in cold areas. They also mentioned that systems with unglazed solar collectors would be advantageous in warm climates. Huang and Chyng [29] developed and investigated DX-SAHPs with a thermosyphon circuit to transmit energy to the hot water storage tank via the condenser. According to investigations, the COP of the heat pump initially rose until it reached above a saturation threshold as solar radiation



Table 4: Continued

Setting of SAHP	Performance	Ref.
H.P.:hermetic rotary compressor Refrigerant: R134a Coll. Type: uncovered solar collector Coll. Area: 1.6 m <sup>2</sup> Storage Tank: 300 L Load: HW	Objective: This experiment aims to evaluate the performance of a DX-SAHP system for water heating under zero solar radiation conditions in the storage tank's static heating mode. The seasonal performance factor of the system was 2.11 and 3.01 at surrounding temperatures of 7.8 and 21.9, respectively. The maximum equivalent SPF for a heating period of the DX-SAHP system tested in this study was 3.01 when 300 L of water was heated from 14 to 55 °C at an average ambient air temperature of 21.9 °C. The time spent on heating was 638 minutes. The lowest system equivalent SPF was 2.11 at 7.8 °C, with mean surrounding air temperature and a heating duration of 963 minutes.	[35]
H.P.: 1100W Refrigerant: R134a Coll. Type: uncovered solar collector Coll. Area: 5.6m <sup>2</sup> Storage Tank: 300 L for HW Load: HW City: Madrid, Spain	Objective: build a theoretical model to calculate the operational variables and consumption of a DHW system using a DX-SAHP The coefficient of performance COP ranged between a minimum value of 1.7 at a temperature of evaporation of -8 °C and a maximum of 2.9 at a temperature of evaporation of 18 °C. At noon, the COP could grow by up to 50%.	[36]
H.P.: 7.5 kW Refrigerant: R407 Load: SH Collector type: unglazed flat plate solar collectors Coll. Area: four solar fields (40.32, 29.12, 22.40, 16.80) m <sup>2</sup>	Objective: A numerical analysis was conducted to evaluate the energy properties of a DX-SAHP that uses R-407C as the working fluid and offers space heating. According to environmental temperature and sun radiation, the COP can range from 2.2 to 4.3. The range of the solar collector's efficiency, between 50% and 149%, is highly influenced by the surrounding temperature and solar radiation.	[21]
H.P.: Compressor speed 2980 rpm, Displacement volume of the compressor (V <sub>a</sub> ) 4.8 cm <sup>3</sup> /rev Coll. Type: flat plate Collector Area: 2m <sup>2</sup> R134a Storage Tank: 150 L Load: HW City: Xi'an, china	Objective: DX-SAHP with solar and air source evaporators connected in parallel as modified DX-SAHP compared to traditional DX-SAHP. The modified system heating time falls by 19.8% compared to the traditional system when the water reaches 55 °C at a low solar radiation of 100 W/m <sup>2</sup> . Meanwhile, the COP generally rises by 14.1%. Because of the presence of the air source evaporator, the modified DX-SAHP system improves the performance of the DX-SHP for water heating systems in low solar radiation environments.	[26]
H.P.: 750W rated power, rotary hermetic compressor. Coll. Type: uncovered solar collectors Coll. Area: two collectors 2m <sup>2</sup> in series Load: SH	Objective: A dynamic model of a DX-SAHP system used for SH under frosting circumstances. Frosting can be delayed, and the evaporation temperature is increased by solar light. The DX-SAHP system's heating performance can also be enhanced. While solar irradiation of 100W/m <sup>2</sup> may avoid icing, COP reduces from 1.97 to 1.89, and the frost thickness after 120 minutes is 0.176 mm when the outside temperature and relative humidity are 1 °C and 70%, respectively. The heating capacity rises from 1082W to 1610W, and the COP from 1.89 to 2.21 as the sun irradiation goes from (100 to 500) W/m <sup>2</sup> .	[37]
H.P.: 750W Coll. Type: uncovered flat plate Coll. Area: 4.2m <sup>2</sup> Storage Tank: 150 L Load: HW	Objective: A new air source hybrid solar-assisted heat pump (AS-SAHP) system comprising a finned tube evaporator and a solar collector evaporator arranged in serial connection. The mean COP climbs from 2.71 to 3.22 as solar irradiation rises from 100W/m <sup>2</sup> to 300W/m <sup>2</sup> and from 2.78 to 3.31 when the surrounding temperature increases from 5 °C to 15 °C. Under different operating conditions, the hybrid source of the AS-SAHP system can serve as a complementary component. The capability of the finned tube evaporator is superior to that of the collector evaporator at solar irradianations of 50 W/m <sup>2</sup> and 100 W/m <sup>2</sup> , while the opposite scenario emerges at solar irradianations of 150 W/m <sup>2</sup> and 200 W/m <sup>2</sup> .	[25]
H.P.: a hermetic reciprocating compressor with a 3500 rpm swept volume of 7.95 cm <sup>3</sup> /rev. Refrigerant: R134a, R290, R600a, R744 and R1234yf. Coll. area: 1.65 m <sup>2</sup> Storage Tank: 200 L Load: HW	Objective: comparison of refrigerants for a modest DX-ASHP. According to the results, the refrigerant R-290 outperforms the others when solar radiation ranges from 300 to 700W/m <sup>2</sup> and the surrounding temperatures range from 10 to 35 °C. However, with solar radiation below 50W/m <sup>2</sup> , the R-134a has a greater COP than other refrigerants.	[38]

## 2.2 Indirect expansion solar-assisted heat pump IDX-SAHP

The IDX-SAHP can be categorized into three types based on the connection between the solar collector and the heat pump: serial, parallel, and complex systems [9]. The parallel mode, dominating 61% of the market, is considered the most practical, with 6% for serial systems and 33% for complicated systems [39].

In the serial system, as illustrated in Figure 4a, the water source heat pump (WSHP) and solar collector are linked in series so that the heat pump evaporator receives its heat from the solar collector indirectly using working fluid [40]. The presence of the heat exchanger, which is often a water tank, distinguishes the series IDX-SAHP from the DX-SAHP. The serial collector energy constrains the serial IDX-SAHP due to this arrangement. In parallel IDX-SAHP, the solar collector and heat pump evaporator are independent components, as depicted in Figure 4b. The collector can provide the requirement when sufficient solar energy is present. At the same time, the heat pump is activated when there is inadequate solar energy, such as at night or on cloudy days, and the solar collector cannot supply the heating requirement. This device uses ambient air or solar radiation to supply thermal energy to the load. The device provides heating energy to the loads through the surrounding air or sunlight.

Due to the benefit of having more straightforward hydraulic connections and system controls than serial and complex systems, parallel systems may be more durable and dependable [41,42]. Another advantage of the system is its capability for the heat pump and solar collector to operate independently at all times, ensuring continued functionality even if one component ceases operation. The complicated system resembles the serial system, but the HP cycle consists of two parallel evaporators. The first evaporator is subjected to ambient air and works as an air source HP, while the second evaporator is installed in the heat exchanger of the collector and works as a water source HP. When one of the evaporators, as mentioned above, is in operation, the second one is isolated using the bypass valve, as shown in Figure 4c. Freeman et al. [43] compared the efficacy of integrated solar heat pump systems for heating residential spaces and household water. They made a comparison between the solar heat pump systems and the conventional systems that can define them as traditional systems that depend on a single source for heating, such as the solar heating system, which depends on the solar collector or the heat pump system, which rely on the heat pump only while the solar heating systems have the two source so they are hybrid systems. The bar chart in Figure 5 illustrates the proportions of the four heat above sources for traditional solar and heat pump systems and the parallel, dual source, and series solar-heat pump systems.

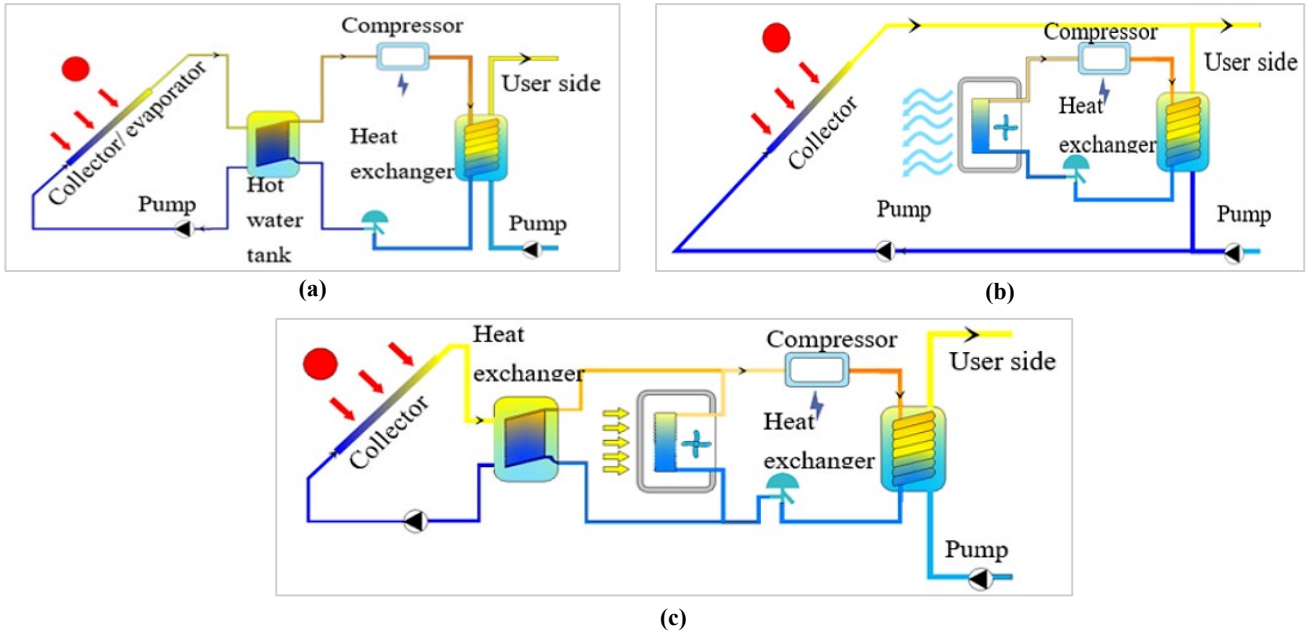


Figure 4: Schematic diagram of (IDX-SAHPs), a) serial mode, b) Parallel mode, c) complex mode [44]

For the parallel, dual source, series, and conventional heat pump systems, the yearly COPS was found to be 2.0, 2.5, 2.8, and 2.1, respectively. The relative COP values for the traditional heat pump and the parallel system heat pump are since the heat pump is forced to function less frequently but under generally more adverse conditions when employed as an auxiliary to a solar system. The COP for series and dual-source heat pumps is significantly higher, as anticipated. This is due to using a solar-heated storage tank as a source. The series heat pump's COP is higher than that of the dual-source system despite the latter's obvious advantage of using a more suitable source--either ambient air or storage. The limitation is that the series heat pump operates effectively only when the source temperature is above 5 °C. In contrast, the dual-source heat pump frequently uses considerably colder ambient air as a source when the tank reaches a freezing point.

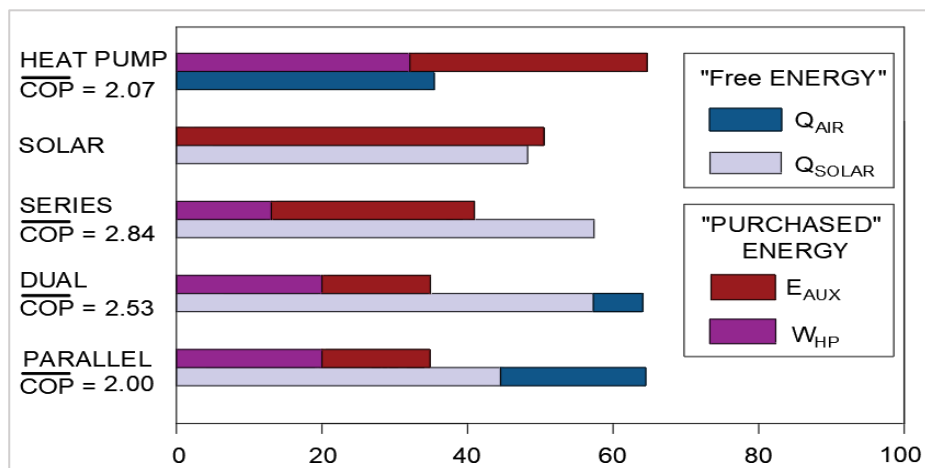


Figure 5: Contributions to heating from all potential sources combined with conventional systems





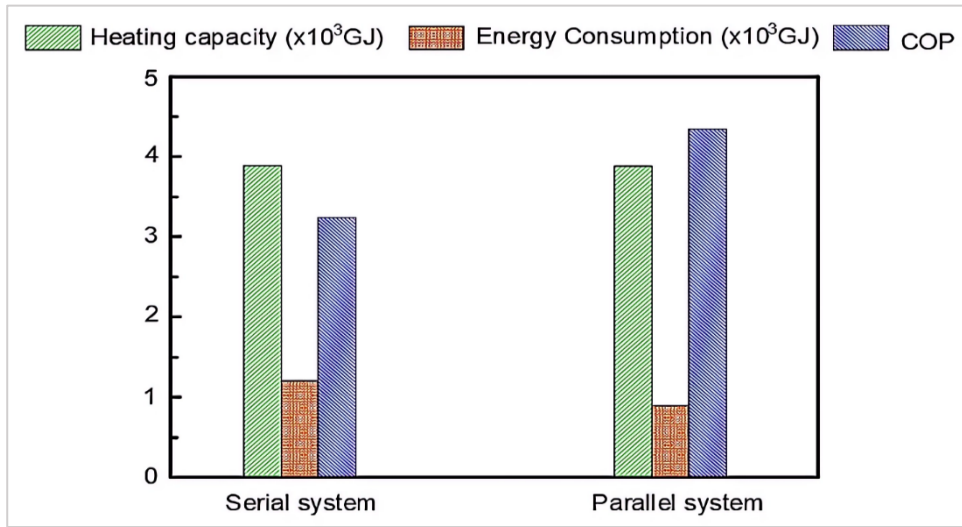
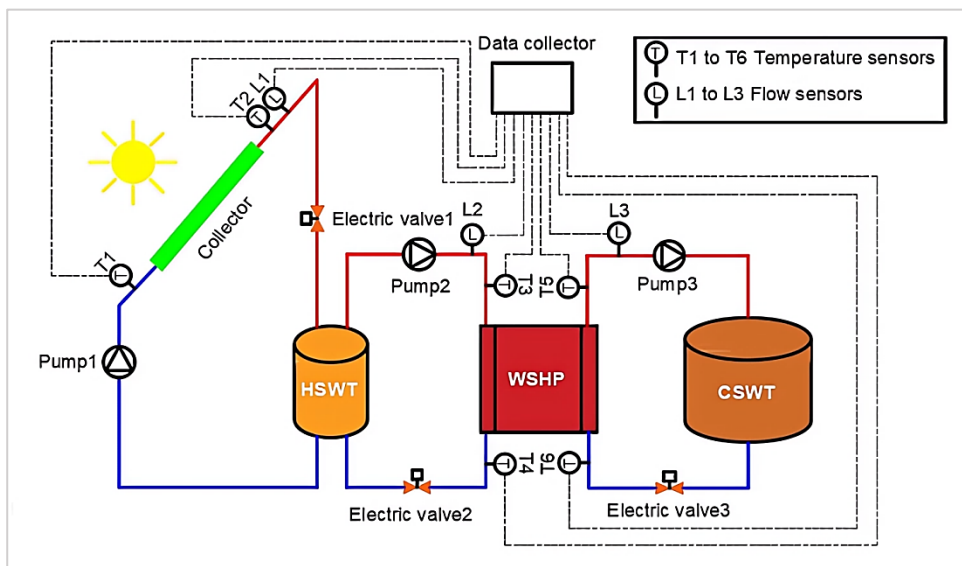
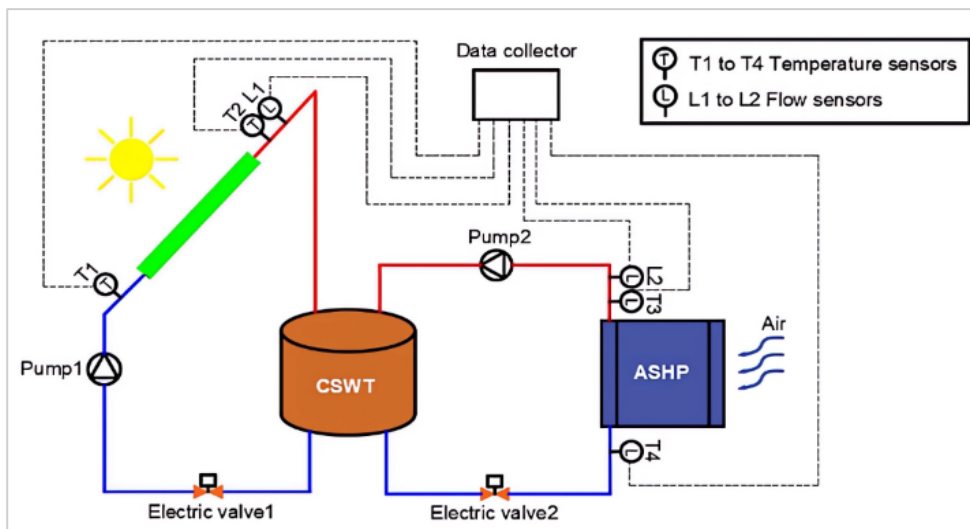


Figure 9: Annual series and parallel performance [18]



(a)



(b)

Figure 10: a) layout diagram of the serial mode of the IDX-SAHP system and b) layout diagram of the parallel mode of the IDX-SAHP system [18]

**Table 5:** Overview of IDX-SAHP

Setting of SAHP	performance	Ref.
H.P.: 16000 W Coll. Type: uncovered and Covered flat plate Coll. Area: 16m <sup>2</sup> Coll. Tilt: 45° Storage Tank: 1000L Load: HW, SH City: Zurich and Madrid	Objective: A general mathematical relation is created to determine whether the thermal performance of these systems is improved by using heat from solar collectors for the heat pump's evaporator rather than directly using it. It is demonstrated that there is a solar radiation threshold above which it is not advantageous to use collector heat for the heat pump's evaporator rather than using it directly.	[49]
H.P.: 617 W Coll. Type: The collectors were replaced with a 3500 W electric heater, and simulations were conducted using a range of collector sizes for the experiments. Coll. Tilt: surface inclined 10o to 80o for simulation. Storage Tank: 270 L for experimental study and varied volumes for simulation Load: HW City: Montreal, Winnipeg, Toronto, Halifax, and Vancouver	Objective: An indirect solar-assisted heat pump prototype ( series mode) was built for the Canadian climate. From the experiment, COP varied between 2.3-3.3. Simulation shows. Toronto's free energy ratio (FEF) varied from 0.501 to 0.524 according to collector inclination. Comparing indirect-SAHP to air source heat pumps, solar domestic hot water systems, and traditional electric systems, annual performance figures were identical to those found in Freeman's feasibility study, which showed that indirect-SAHP had the lowest life cycle cost in most cities. Though different parts were only marginally	[40]
H.P.: 1491W Coll. Area: 12 collectors, each 1.64m <sup>2</sup> Coll. Tilt: 50° Storage Tank: 2000L Load: SH City: Erzurum, Turkey	Objective: An experimental investigation of a solar source heat pump system was conducted. The monthly average SPF ranged from 2.5 to 2.9. The monthly mean COP ranged between 3.3 and 3.8. Solar source heat pump systems offer significant environmental benefits compared to traditional systems.	[50]
H.P.: 5000 W combined to a borehole of 75 m via heat exchanger Coll. Area: 11 m <sup>2</sup> Storage Tank: 750 L Load: HW, SH City: Herford, Germany	Objective: There have been two presentations on solar and heat pump systems. A borehole heat exchanger is used in the first, while a gas boiler and an air-to-water split heat pump are included in the second. Long-term heat pump operation with a high system performance factor (SPF) is made possible by the solar regeneration of the geothermal probes, which maintains a high ground temperature. The SPF is greater than five. Due to solar gains, the SPF for the entire system may be raised by an average of 35%, confirming the simulations' results.	[51]
H.P.: 14610 W Coll. Type: Photovoltaic/Thermal Collector area: 600 m <sup>2</sup> Coll. Tilt: 23° Storage Tank: 60 m <sup>3</sup> Load: HW City: Hong Kong, Paris, Lyon, Nice	Objective: This study aims to produce a realistic case study of a hybrid PV/T solar-assisted heat pump (SAHP) system for producing hot water for a sports center. The average coefficient of performance is 4.9. In Hong Kong, PV/T collectors have an overall efficiency of up to 76%. In Nice, the worldwide fractional energy saving factor can reach up to 75 percent. For Hong Kong, the payback period is 10.52 years.	[52]
Coll. Type: Flat plate collector Coll. Area: 2 x 2.58 m <sup>2</sup> (parallel) Coll. Tilt: 35o Storage Tank: 280 L Load: HW City: Athens	Objective: An investigation is conducted on the efficiency of a combined solar thermal heat pump hot water system (Parallel IDX-SAHP). Energy saved 70% for Athens climate, and the COP was 2.3. Solar contribution = 68.4% ,Auxiliary contribution = 31.6% (high radiation day) Solar contribution = 41.3%, Auxiliary contribution = 58.7% (low radiation day) Eff_solar= 0.45.	[53]
Coll. Type: flat plate Coll. Area: 3.2m <sup>2</sup> Storage Tank: 300L Load: HW, SH, SC	Objective: A unique hybrid system that combines a multi-functional heat pump and solar thermal collecting system. Running the multipurpose heat pump and solar thermal collecting system together in solar water heating mode can be an energy-saving technique. The COP climbs from 2.35 to 2.57, and the heating capacity increases from 1.89 kW to 2.09 kW when solar irradiation increases from 0W/m <sup>2</sup> to 800W/m <sup>2</sup> .	[54]

Table 5: Continued

Setting of SAHP	performance	Ref.
H.P.: 9 kW Coll. Type: Flat Plate Collectors (FPC) and Evacuated Tube Collectors (ETC) Coll. Area: 8m <sup>2</sup> Storage Tank: 23.4m <sup>3</sup> Load: HW, SH City: Chile	Objective: shows the TRNSYS modeling of a SHP system created for a five-story residential construction. For the DHW demand and the heating requirement, two parallel SHP systems with air-to-water heat pumps are simulated so that the hot water in the storage tank in one system is used for DHW and in another system is used for SH. SPF <sub>heat</sub> : 4.64 using FPC and 4.88 using ETC. SPF <sub>DHW</sub> : 3.93 using FPC and 4.27 using ETC. SF <sub>heat</sub> : 13.1% using FPC and 19% using ETC. SF <sub>DHW</sub> : 51.6% using FPC and 58.5 using ETC.	[55]
H.P.: compressor, hermetic, piston compression, 1/6 HP Refrigerant: 134a Coll. Type: flat plastic collectors Coll. area: 3 x 1.05 m <sup>2</sup> Coll. Tilt: 33o Storage Tank: 250 L Load: HW	Objective: A comparison test was performed between a combination system (solar collector and heat pump) and a regular supplementary heating system (high electric power). In laboratory tests, the mean COP was 2.15. The COP with forced circulation was 2.34, almost a 9% increase. The SAHP system consumed 54.9% less energy than experiments in which an electrical heater was used as a source of additional heating.	[10]
H.P.: 7 kW Coll Type: evacuated tube solar collectors Storage Tank: 0.75 m <sup>3</sup>	Objective: The effectiveness and viability of the solar air source heat pump (SASHP) heating system are investigated using data from a low-energy residential building in Xining City. During the heating season, the average COPs of the SASHP and ASHP systems are 6.22 and 2.97, respectively. The SASHP system has a COP of 109.43% greater than the ASHP system's. Solar radiation has the biggest impact on the overall solar fraction, which is 55% during the heating season. In the event of a 20-year service life, the SASHP system's energy consumption and yearly cost are, respectively, 55.38% and 9.7% lower than those of the ASHP system.	[14]
H.P.: the rated input power of the heat pump was 1750 W, Coll. Type: flat plate collector Coll. Area: 12 m <sup>2</sup> (6*2m <sup>2</sup> ) Storage Tank: 0.3 m <sup>3</sup> Coll. Tilt: 28o	Objective: Several connection techniques, including SHW, ASHP, parallel mode, series mode, and preheating type connection method of solar hot water as air source heat pump's heat source, are offered for a hybrid sun hot water and air source heat pump (HSAHP) combined heating system. The HSAHP, parallel, PASAHP, and series modes' respective COPs were 3.60, 3.32, 3.11, and 3.36. Compared to the parallel, PASAHP, and series modes, The values of SPF for the HSAHP were 8.4%, 15.8%, and 7.1% higher, respectively.	[56]
H.P.: The input power is 1 kW Coll. Type: evacuate tube coll. Coll. Area: 16 m <sup>2</sup> Storage Tank: Volume is 1.3 m <sup>3</sup> , heat storage capacity is 300 MJ (phase change material)	Objective: Examine the combination of a phase change thermal storage system with a solar energy system and a heat pump system. The system uses roughly 72.8% less electricity for heating than a single heat pump. The daily operating costs are only 41.2% of those of a single heat pump heating system. The solar collector's efficiency can reach 59.8 percent. The system's solar energy fraction of heat supply is 27.2%. The mean COP <sub>system</sub> reaches 3.79	[57]
H.P.: Replace the evaporator and condenser's conventionally costly, bulky, and metal-intensive plate heat exchangers with tubular flexible heat exchangers, and install the compressor inside the evaporator's flexible heat exchangers, which are arranged in a circle around the filter. Coll. Type: glazed flat collector Storage Tank: 50 L	Objective: The accessibility of the solar-heat supply system in the cool region of Kazakhstan with little sun radiation was investigated. The effectiveness of 2.40 and 2.53 has been observed. For a flat plate collector, the efficiency ranged from 40% to 50% depending on where the tubes were placed concerning the absorbing plate. According to experimental findings, the power produced by a flat solar collector ranges from 1.6 to 2.2 and from 2.3 to 3 kW/m <sup>2</sup> .	[16]

### 3. Thermal performance measures

The thermal performance of the SAHP was evaluated using various energy indicators, as outlined in the literature, particularly in Tables 2 and 3. The definitions of these indicators are given below:

For the individual components of the systems, such as the heat pump and the solar collector, the coefficient of performance (COP) and collector efficiency  $\eta$  are used, representing each component's performance separately. These variables are computed by Equations 1 and 2.

$$COP = \frac{\dot{Q}_{Load}}{\dot{P}_{comp.}} \quad (1)$$

where  $\dot{Q}_{Load}$  represents the heat pump's rate of load heating in kJ/h and  $\dot{P}_{comp.}$  represents the power consumption rate by the compressor in kJ/h [7].

$$\eta = \frac{\dot{Q}_{coll}}{A_{coll} \cdot I} \quad (2)$$

where  $\dot{Q}_{coll}$  is the rate of useful solar energy collected by the solar collector in kJ/h,  $A_{coll}$  is the area of the solar collector in m<sup>2</sup>, and  $I$  is the solar radiation falling on the collector in W/m<sup>2</sup> [58].

The performance of a complete SAHP system is measured using additional measures, including the seasonal performance factor (SPF), the free energy fraction (FEF), and the solar fraction (SF). The SF is the proportion of usable solar energy captured by the collectors, measured as  $Q_{coll}$ , in kJ, to the overall energy loads such as space heating or cooling and/or hot water for domestic uses,  $Q_{Load}$ , in kJ. In the mathematical model as in Equation 3 [59].

$$SF = \frac{Q_{coll}}{Q_{Load,total}} \quad (3)$$

The solar fraction solely quantifies the proportion of solar energy captured by the collector and does not account for the free energy obtained from the surrounding air; hence, a new metric should be used, that is, the free energy fraction FEF [60] as defined in Equation 4, which is used to calculate this fraction

$$FEF = \frac{Q_{coll} + Q_{air}}{Q_{Load,total}} = \frac{Q_{Load,total} - Q_{aux} - P_{comp} - P_{pump}}{Q_{Load,total}} \quad (4)$$

where  $Q_{air}$  represents the amount of energy absorbed from ambient air (kJ),  $Q_{aux}$  indicates the supplementary source of energy (kJ),  $P_{pump}$  is the electrical energy needed to operate the pump and circulate the operating fluid.

The SPF in Equation 5, which is the proportion of the overall loads fulfilled by the system to the overall electrical energy consumed, is one method highlighted in several studies in the literature to assess the effectiveness of SAHPs [61]. The SPF is suitable for summarizing the effectiveness of an entire SAHP system, similar to how the FEF is used.

$$SPF = \frac{Q_{Load,total}}{Q_{aux} + P_{comp} + P_{pump}} \quad (5)$$

#### 4. Types of refrigerants utilized by SAHPs

The heat pump is considered one of the main components of the solar-assisted heat pump system. Since the refrigerant serves as the working fluid of the heat pump, it significantly influences the heat pump's performance. Thus, several studies have focused on exploring various types of refrigerants to attain optimal heat transfer rates and coefficient of performance. The operational fluid used by SAHPs must possess a large thermal conductivity, a large critical temperature, and an enthalpy of evaporation. Furthermore, to operate the refrigerant, particular characteristics are needed, such as an exceptionally low specific volume capacity, low point of freezing, and viscosity, as the heat pump uses less energy.

Depletion of the ozone layer and environmental degradation is the second challenge that has to be considered relating to refrigerants in choosing their standards. The two prominent kinds of refrigerants exploited by SAHP systems are mixed and plain. Mixed refrigerants, in particular, are currently being considered for SAHP systems since they are efficient, safe, and environmentally friendly. Chata et al. [62] studied the thermal performance of a DX-SAHP for different refrigerants; they used two collector types: uncover and cover collectors. R-12, R-22, and R-134a were shown to yield the most significant COP. R-410A is more effective than R-407C or R-404A for mixed refrigerants but 15-20% less effective than R-134a.

Mohanraj et al. [63] compared R-22 and a combination of R-407C for SAHPs. The combination's energy performance ratio (EPR) was discovered to be 2-5% less than R-22. The mixture was claimed to have a minor overall equivalent warming effect compared to R22 under leaky circumstances. Even though the effectiveness of the mixture-type refrigerants was revealed to be inferior to that of traditional primary refrigerants, the results were optimistic, showcasing the superior potential of the mixture over that of competing options.

#### 5. TRNSYS software

Several Researchers in the literature used TRNSYS software to simulate their works. TRNSYS software is a highly adaptable, visually based software environment that simulates the dynamics of transient systems. TRNSYS contains a large library of components, each of which symbolizes the performance of a certain aspect of the system. The standard library contains over 150 models ranging from solar collectors to pumps, heat pumps to multizone buildings, weather data processors to economics procedures, and basic HVAC equipment to cutting-edge developing technologies. The analyzed systems are made up of suitably connected components (types). Each element (type) includes a specific executable application that runs in the

foreground of TRNSYS. Several parameters must be regulated by the user and connected properly between components to model the system appropriately. Table 6 illustrates some components (Types) of TRNSYS used in the literature.

**Table 6:** Some components of TRNSYS used in the literature

Component name	Type
Solar collector	1b, 832, 538, 539
Storage tank	4b, 340, 534
Water-to-water heat pump	668
Air to water heat pump	877, 941
Building heating load	12c, 56
DHW load	14b
Water pump	3b, 110
TMY2 (weather data)	109

## 6. Challenges and future work

According to the outcomes of numerous studies, there is no optimal SAHP system setup because the configuration varies with the size of dwellings, load, and weather conditions. Similarly, forthcoming research endeavors must employ a standardized assessment methodology to assess the effectiveness of SAHPs. Considering everything, the study specifies that SAHPs offer a promising potential as a flexible and feasible option for different climates. The main purpose of the SAHP system is to reduce electricity consumption, which represents the running cost. At the same time, the modifications of these systems required adding components, which increased the systems' capital cost. So, the investigations should also include an economic analysis as the long-term cost of the system and the potential cost savings will dictate the feasibility of implementing the system in residential houses.

The refrigerant, the working fluid of the heat pumps, must be environment-friendly. So it would be worth investigating replacing 134a refrigerant with a different working refrigerant such as R744 (CO<sub>2</sub>) as R-134a will be banned worldwide.

Besides the traditional study approaches to SAHPs, the following domains may be addressed in the future:

- 1) Solar-assisted heat pump system with intelligent management and monitoring from a distance system.
- 2) Heat pumps with several sources.
- 3) Heat pump operation that is low-carbon and energy-efficient.
- 4) Sophisticated thermal storage and exchange unit technological devices.

## 7. Conclusion

SAHPs combine a solar heating system and (H.P.), with the benefits of energy at low temperatures harvesting, generating hot water at high temperatures, decreasing the area of the solar surface, large solar collector efficiency, and enhancing coefficient of performance (COP).

This study presents numerous works on SAHP systems for low-temperature water heating applications. Additionally, the system's functioning was described and classified into two types: direct expansion solar-assisted heat pump and indirect expansion solar-assisted heat pump based on the connection between the collectors and the heat pump's evaporators. In the DX-SAHP system, the solar collector represents the heat pump's evaporator so that the refrigerant flows directly through the collector. The utilization of solar collectors as evaporator units significantly boosts the overall efficiency while reducing the associated expenditure in terms of payback period due to the high evaporation temperature and the high COP of the heat pump. At the same time, according to previous studies, the performance of DX-SAHP can vary significantly due to the influence of sunlight, giving the refrigerant the ability to move directly within the collector. Parallel and series connections of the DX-SAHP are used to overcome the DX-SHPWH system's performance decline during periods of low solar radiation by adding the air source evaporator. The parallel DX-SAHP has two evaporators: the solar source evaporator and the air source evaporator. The two evaporators are combined in parallel so that the M-DX-SHPWH system operates in two modes: (1) single solar collector mode (SM), which is activated when solar radiation is significant enough to heat the water efficiently, and (2) combination mode (CM), which is activated when solar radiation is insufficient to improve the heat pump's performance. The addition of the air source evaporator in parallel connection enhanced the performance of the DX-SAHP system with a low solar radiation of 100 W/m<sup>2</sup>. The COP increased by 14.1%, and the heating time fell by 19.8% compared to the system with solar source evaporator only.

The series DX-SAHP also consists of two evaporators; however, they are arranged in series, meaning that the refrigerant flows from the solar collector into the air source evaporator, where the improved heat transmission of the finned tube evaporator allows efficient heat recovery from the surrounding air. Therefore, a hybrid source can function complementary depending on the operating environment. This is because the collector evaporators are less effective than finned tube evaporators in low sun irradiation, and the opposite is true in high solar irradiation. The air solar-solar assisted heat pump (AS-SAHP) was compared with DX-SAHP and ASHP under different ambient temperatures. The DX-SAHP has the largest power usage, followed by the AS-SAHP system, while the ASHP system has the lowest power consumption. The AS-SAHP system has the highest COP, followed by DX-SAHP, while the ASHP system has the lowest COP. The main objective of the study is to guarantee DX-SAHP's efficacy and durability in several areas where the DX-SAHP system is significantly impacted by sun radiation, which causes regional variations in performance. The DX-SAHP system's refrigerant enters the solar collector directly, preventing heat loss through the intermediary heat exchanger. Nevertheless, its lengthy refrigerant circulation loop can result in refrigerant leaks and

entrapment in the condenser and evaporator. Consequently, researchers have turned their focus to the IDX-SAHP. In indirect expansion solar-assisted heat pump systems, the solar collector is distinct from the heat pump cycle, introducing a second working fluid, typically glycol, to transfer heat from the solar collector. The integration of thermal energy from the solar collector into the system varies. IDX-SAHP systems are further classified into serial, parallel, and complex configurations. In serial IDX-SAHP, the solar energy is delivered to the heat pump evaporator using a heat exchanger, hence enhancing the COP of the heat pump due to the high evaporation temperature. In the parallel IDX-SAHP mode, the solar collector and the heat pump supply heat individually; hence, they can function separately or in conjunction simultaneously. Finally, the complicated system combines the two modes.

Certain researchers examine the performance of SAHP systems for specific configurations individually while proposing enhancements such as incorporating double storage tanks or employing phase change materials as the working medium within the storage tanks. At the same time, other studies compared various configurations of SAHP systems. The survey outcomes comparing parallel and series modes showed that, over a year, the parallel mode of IDX-SAHPs outperformed the serial mode in the Xi'an area. However, during the winter season, the serial IDX-SAHP system outperformed the parallel IDX-SAHP system in terms of efficiency. The parallel system has a mean COP of 4.34 and uses 894 GJ of energy annually. The serial system has a mean COP of 3.23 and an annual energy consumption of 1200 GJ. During year-round operation, the parallel IDX-SAHP system performs more energy efficiently than the serial system, suggesting that the parallel system is a better fit for the Xi'an district.

Based on the literature, using the second tank enables the collection of more solar energy. It is designed to float in temperature, earning the name Float Tank. The float tank improves the efficiency of the solar collector because it is cooler than the DHW tank and has lower thermal losses. However, the presence of another tank for storage necessitates additional regulation options. According to the findings, the two-tank SAHP system has the potential to save a significant amount of energy, particularly when used in big thermal solar collector (STC) areas. It can also save almost 12% of electricity for the same STC. The two-tank SAHP system is more appropriate for a district heating application or multi-residential building in terms of load size.

A unique hybrid system that combines a multi-functional heat pump and solar thermal collecting system is presented in the literature. The heat pump is equipped with dual evaporator water sources, capable of harnessing solar energy from the hot water storage tank and utilizing an outdoor air heat exchanger that draws on ambient air for heat. Furthermore, it features two condensers: an indoor heat exchanger for space heating and cooling purposes and a submerged coil within the hot water storage tank dedicated to domestic use. Operating the multi-functional heat pump system and solar thermal collecting system concurrently can be an energy-efficient way for solar water heating mode. Using a phase change thermal storage tank in a system surveyed in the literature followed this arrangement. The solar collector can deliver heat either to the phase change thermal storage tank or directly to the heat pump's evaporator, which then provides heat directly to the building.

Moreover, an electric boiler is attached to the phase change thermal storage tank to supply it with heat when solar energy is unavailable. The findings indicated a remarkable reduction of approximately 72.8% in electricity consumption for heating compared to a single heat pump system. Besides, the daily operational expenses were only 41.2% of those associated with a single heat pump heating system. According to peer-reviewed research, solar thermal energy considerably affects the effectiveness of the heat pump and collector separately and the overall SAHPs. However, more sophisticated configuration classes of SAHPs have been shown to perform more effectively than the conventional basic types in reported COPs, which triggers the interest of future researchers. The energy sources and the overall energy load on all SAHP systems must be described for system assessment, as these factors can differ based on system components, building loads, and climate. Accordingly, assessing factors such as SF, FEF, or SPF for the entire system is essential. While the performance of individual components is vital, evaluations of heat pumps and solar collectors not only designate the power needed to fulfill the loads. The current study deals with an analytical and experimental study of the performance of the solar air heat pump system's main components, specifically the collector/evaporator, compressor, and heat exchanger, as well as the refrigerant's characteristics. To obtain the greatest energy savings, more emphasis should be placed on intelligent control, optimal system working, and interaction with buildings. Furthermore, more detailed economic and feasibility evaluation studies should be conducted for various SAHP systems.

**Nomenclature**

$A_{coll}$	Area of solar collector	$Q_{air}$	The energy absorbed from ambient air
ASHP	Air source heat pump	$Q_{aux}$	The supplementary energy source
COP	Coefficient of performance	$Q_{coll}$	Usable solar energy captured by the collectors
DX-SAHP	Direct expansion solar-assisted heat pump	$Q_{Load,total}$	Overall energy loads
DX-SAHPs	Direct expansion solar-assisted heat pump system	$\dot{Q}_{coll}$	The rate of useful solar energy collected by the solar collector
ETC	Evacuated Tube Collectors	$\dot{Q}_{Load}$	The rate of the heat pump's heat to the load
FEF	Free energy fraction	SAHP	Solar-assisted heat pump
FPC	Flat plate collector	SAHPs	Solar-assisted heat pump system
H. P.	Heat pump	SC	Space cooling
HW	hot water	SDHW	Solar domestic hot water
I	Solar intensity	SF	Solar fraction
IDX-SAHP	Indirect expansion solar-assisted heat pump	SH	Space heating
WSHP	Water source heat pump	$SPF_{HP}$	Heat pump's seasonal performance factor.
$P_{pump}$	the electrical energy needed to run the pump	$SPF_{system}$	System's seasonal performance factor
PV	Photovoltaic	ST	Solar thermal
PV/T	photovoltaic/thermal heat pump	$\eta$	collector efficiency
$\dot{P}_{comp.}$	the rate of electricity consumed by the compressor		

### Author contributions

Conceptualization, G. Mohammed. A. Saleh and A. Khalifa; formal analysis, G. Mohammed, A. Saleh, and A. Khalifa; investigation, G. Mohammed.; methodology, A. Khalifa.; project administration, A. Saleh and A. Khalifa.; resources, G. Mohammed.; supervision, A. Saleh and A. Khalifa; visualization, A. Saleh.; writing—original draft preparation, G. Mohammed.; writing—review and editing, G. Mohammed. All authors have read and agreed to the published version of the manuscript.

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The data that support the findings of this study are available on request from the corresponding author.

### Conflicts of interest

The authors declare that there is no conflict of interest.

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