Solar assisted heat pump systems for low temperature water heating applications: A systematic review

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Abstract

Combination of solars thermalolar thermal collectors and heat pumps in a single solar assisted heat pump (SAHP) system has been widely used for various purposes including water heating. International Energy Agency, Task 44 of the Solar Heating and Cooling (SHC) Programme, has been working on methods towards most effective use of solar heat pump systems for residential use. The current work aims at reviewing the past and present work conducted on the SAHP systems for low temperature water heating applications. The review approach is based on a visualisation scheme to systematically represent and classify concepts of SAHP systems. Specifically, the key performance data from a number of studies are highlighted and various configurations are compared in order to gain accurate and deep intuitive understanding of SAHP systems. The review faithfully states that having a variety of configurations, parameters and performance criteria may lead to a major inconsistency that increase the degree of complexity to compare and analyse the studies of different systems. Highlights•A visualization scheme was introduced for systematic classification.•SAHP concepts were introduced.•A number of past and present studies were reviewed.•International Energy Agency Task 44 of the Solar Heating and Cooling (SHC) Programme was briefly provided.•Concluding remarks were outlined.

Keywords: Solar assisted heat pump; waterWater heating; lowLow temperature application; systematicSystematic classification

1 Introduction

Global energy consumption has increased substantially in recent decades. Conventional fossil fuel based energy sources cover a large portion of the worldwide energy use. In 2008, the total global energy consumption was about 17 TW (=1.7 × 10(=1.7×10^{13}) with 81.4% from fossil fuels [1]. However, burning or combusting fossil fuels causes global warming as a result of greenhouse effect, air pollution, and acid rain by depleting carbon dioxide and other harmful gases to the environment [2]. Since 1750, 31% increase in the atmospheric concentration of CO_2, above pre-industrial level, is noted while fossil energy consumption has increased most in 2000–2008. This growing demand for fossil fuels may cause a major disruption and endanger the energy supply chain. The major concerns of depletion in fossil fuel based energy sources, economic and environmental problems associated with the combustion of fossil fuels have led to the critical societal need to transition to renewable energy resources such as solar, wind, and hydropower in recent years [3].

In 2013, UK'sUK′s total energy consumption was 205.9 million tonnes of oil equivalent (mtoe). About 31.7% of this total energy was consumed in domestic applications. Space heating alone accounts for 53% of the energy consumed in a typical UK household while it is estimated that about 13.7% is for low temperature (<80 °C) water heating applications in which energy demand is primarily satisfied through either natural gas or electrical heaters [4]. However, use of conventional source of energy based systems leads to increased greenhouse gas emissions into the atmosphere. A typical natural gas water heater releases around 2 t CO_2 annually. Electric hot water systems are having more harmful effect for about three times the emission of CO_2 for each kWh of electrical energy, compared to natural gas water heaters. In spite of low capital cost of this fossil fuel based systems, due to implicit environmental cost for remedy or separation of CO_2 fossil fuel burners it is worth the time, money or effort to search for less expensive, environmentally friendly alternatives such as solar energy, one of the most viable renewable based energy sources [3].

A solar-assisted heat pump system (SAHP) is a particular technique to reduce or eliminate the primary energy (coal, natural gas, etc.) consumption through substitution of renewable based energy sources to achieve reduced CO_2 emission. The system is able to convert and transport thermal energy from the sun to water or working medium or absorbers. In addition, this system allows transferring heat for storage purposes. Through modification in the system configuration, reduction in the number of system units and cost, and enhancement in efficiencies would be achievable. There has been a growing interest for such hybrid systems with a variety of system configurations for various climate conditions. A number of research studies have been presented in the literature on fundamentals of system design, modelling and optimisation of performance characteristics, as well as experimental investigations of pilot scale designs [5]. The main objective of this study is to present a systematic review of the research and developments on solar assisted heat pump systems for low temperature water heating applications. This study is, therefore, arranged into three main parts as follows:

- Solar assisted heat pumps and low temperature heating applications
- Design components and configurations
- Thermal performance characteristics of SAHP

2 Classification method

There are different types of system classifications designed in various categories. Solar assisted heat pump systems can be classified by the type of applied components like collector types, flat plate, glazed-unglazed etc. or alternatively type of refrigerant used in the heat pump cycle. However, the efficiency of such systems immensely depends on environmental conditions, system and component size and load characteristics. Therefore, there ~~wouldn't~~ would not be any simple classification method to conform the public to an easy communication. Yet, these various specifications, in literature, to compare the SAHP systems are systematically shown by Frank et al. [6]. A comprehensive table that displays research, design and development work and an overview of design approach such as refrigerant type, with or without storage, the location of the storage, can indicate particular know-how about solar heat pump applications. Hence, a methodical display in Table 1 was presented from literature including system information and boundary conditions regarding climate.

Table 1 System classification table – a sample of the literature study to provide information about system concepts.

alt-text: Table 1

	Şevik et al. [7]	Fernández-Seara et al. [8]	Hawlader et al. [37]	Badescu et al. [10]	Cerit et al. [11]	Huang et al. [12]	Li et al. [65]	Chow et al. [14]	Chen et al. [15]	Panaras et al. [16]	Zhang et al. [51]	Ji et al. [17]
~~SYSTEM INFORMATION~~System information												
~~1.Solar~~ 1. Solar collector type												
Direct evaporation (uncovered)		X	X									
Flat plate (uncovered)									X			
Flat plate (covered)	X						X	X		X		X
Evacuated tube						X					X	
Solar air collector			X	X								
Roll-bond					X							
~~2.Solar~~ 2. Solar heat sink												
Domestic hot water	X							X				
Space heating	X	X	X	X	X			X	X		X	X
Heat pump evaporator		X	X	X	X						X	X
Boreholes									X			
Storage (cold side of HP)				X		X	X	X		X		
~~3.Heat~~ 3. Heat sources for heat pump												
Solar collector (direct evaporation)		X	X	X	X			X				X
Solar collector (heat exchanger)	X					X	X	X	X		X	
Air			X	X						X		

~~4.Refrigerant~~4. Refrigerant (ns if not specified)	ns	R134a	R134a	R114	R134a	R22	R22	R22	ns	ns	ns	ns
~~5.Heat~~ 5. Heat pump sink												
Domestic hot water		X			X		X	X		X	X	X
Space heating	X		X	X		X			X			
~~6.Storage~~ 6. Storage concept (cold side HP)												
None		X	X		X							
Water	X					X	X	X	X	X	X	X
Seasonal storage				X								
~~7.Storage~~ 7. Storage concept (load)												
None	X		X			X						
Water		X		X	X		X	X	X	X	X	X
~~8.Additional~~ 8. Additional heating (backup)												
Electricity (direct)	X	X	X	X	X	X	X	X	X	X	X	X
~~BOUNDARY CONDITIONS~~Boundary conditions												
~~9.Climate–Country~~9. Climate-country	TR	SP	SIN	US	TR	TWN	CN	HK	HK	GR	UK	CN
~~10.Application~~10. Application												
Temperature (°C)	45	55	40	22	ns	80	36	33	ns	55	45	30
Domestic hot water		X			X		X	X	X	X	X	X
Space heating-water									X			
Space heating-air	X		X	X		X						

3 Systematic visualisation scheme of solar assisted heat pump concepts

System classification for various solar assisted heat pump concepts is performed by considering distinctive system configuration features like collector type, heat sink of the system, storage concept etc. The table presented in Section 2 provides a piece of information for a plain classification method. In the energy flow like visualisation scheme, only solar assisted heat pump system is illustrated rather than a whole building. As a result of analysing many combined solar and heat pump systems, it is found that solar assisted heat pumps systems comprise five recurring components namely solar collector, heat pump and backup heater, along with storages either cold or load or both side of the heat pump units. Fixed positions for all these components are defined although specifications, like type of the collector, may vary in different configurations.

Assorted colours used in the visualisation scheme distinguish the energy flow in the system as final (grey), boundaries (grey background), environmental energy (green), useful energy (red), energy converters (orange) and storages (blue). Yet colouring is an additional feature as it is not essential to comprehend the concept. The final energy (to be purchased such as electricity) is shown at the system boundary on the left-hand side where useful energy (i.e. domestic hot water-DHW) flow is introduced on the right. Environmental energy sources enter the system from the top while any losses would be downwards although no losses leaving the system depicted as being redundant to system characterisation. Lastly, the connection of system components is illustrated to analyse and compare the concepts. Each line style aims at the carrier medium, excluding driving energies mostly without mass i.e. solar radiation.

One should remark that all potential operating modes of one combined solar and heat pump system is presented simultaneously by one flow chart visualisation. All components in a solar heat pump concept are depicted as filled; others remain shaded as placeholders for orientation and comparison purposes.

A simple example of a visualisation scheme is provided in Fig. 1 to comprehend the classification method. In Figs 2–4, widely available combined solar and heat pump configurations are presented through the visualisation scheme proposed. The figures offer the possibility to make a comparison among the solar assisted heat pump systems. Additionally, energy flows usually from left-to-right and ~~up-down~~up–down directions in the arrangement of the visualisation scheme, despite a range of combinations may be exceptional.

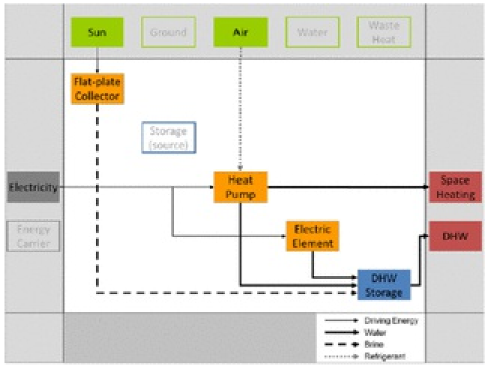

Fig. 1 Introductory sample of the visualisation scheme [18].

alt-text: Fig. 1

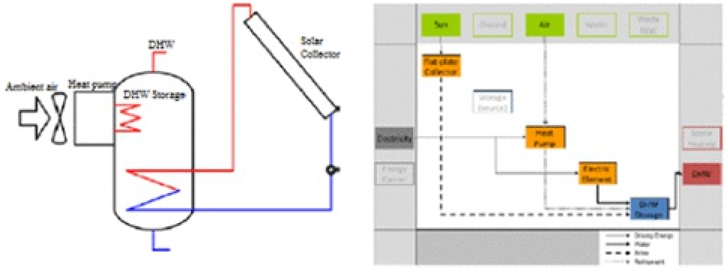

Fig. 2 Solar heat pump system with a flat-plate collector and a direct-evaporation air source heat pump unit along with the condenser immersed in a DHW storage. This system is exclusively designed for DHW applications [18].

alt-text: Fig. 2

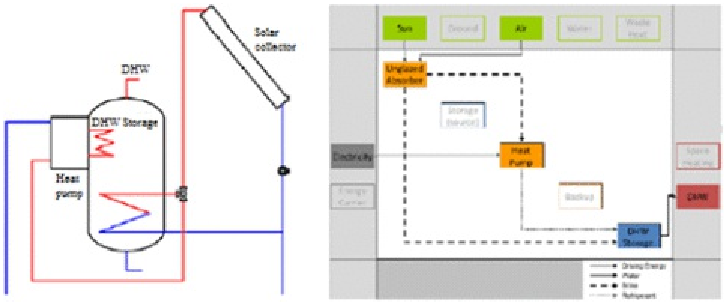

Fig. 3 Solar heat pump system with an unglazed collector and a heat pump unit along with the condenser immersed in a DHW storage. This system is exclusively designed for DHW applications [18].

alt-text: Fig. 3

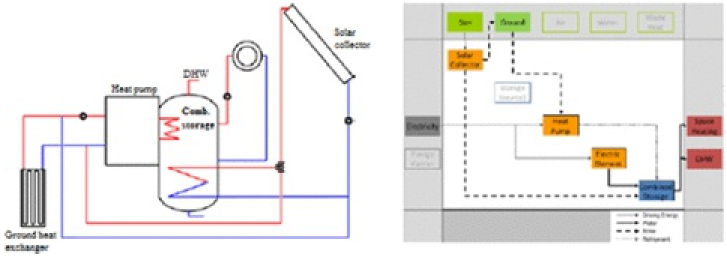

Fig. 4 Solar heat pump system with an unspecified collector and a heat pump unit along with the condenser immersed in a combined storage tank. This system is designed for DHW preparation as well as space heating applications [18].

alt-text: Fig. 4

4 Solar assisted heat pump systems

The basic principle of solar thermal energy systems is to collect solar energy in the form of heat. A solar collector comprises pipes running behind an absorber and transferring a working fluid. The working fluid absorbs the energy in heat form and carries to thermal energy storage or to a heating/cooling system [19] as a schematic of indirect (via heat exchanger) solar DHW system can be found in Fig. 5. So, the solar energy system captures heat during the periods when solar energy is available. Else, a heat pump is a device that transports heat from a source to other by running a refrigeration cycle. An important thermodynamic fact is that heat flows from warmer to cooler however; a HP reverses the flow direction and pumps the heat to move. A refrigerant, also known as working fluid, in a heat pump cycle is compressed to liquid state then expanded to a ~~vapor~~vapour state to absorb and remove heat [20]. Combined solar thermal energy technologies and heat pump into a SAHP system is a promising application offering great potentials to offset low temperature ~~(< 80~~(<80 °C) applications like DHW, space heating etc. A benefit to combine solar thermal and heat pump systems together is to improve the performance of the subsystems, eventually result in enhancing performance of the SAHP system as a whole.

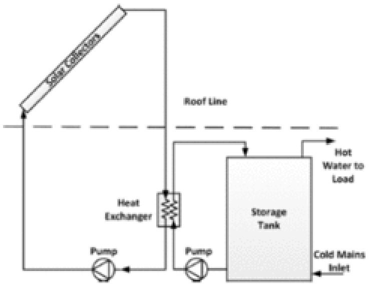

Fig. 5 Indirect solar DHW system [19].

alt-text: Fig. 5

The system configurations are characterised by the method the solar thermal and heat pump components interact by Freeman et al. [27]. The solar thermal collector and heat pump units can independently supply useful energy through charging one or more heat storages. This configuration is mostly stated as ‘parallel’ and in these systems; the collectors would feed the storage and if the energy level is insufficient then an auxiliary heat source such as an air-source heat pump or ground heat exchanger would run in parallel to the collectors to attain the required amount of energy. A schematic of a parallel system is presented in Fig. 6. The solar thermal collector can act as a heat source of the heat pump unit, either primary or supplementary, and either directly or via buffer storage. This concept is denoted as ‘serial’. When coupled in series, the captured heat energy is fed into the evaporator of the heat pump by working fluid. Then, the evaporator receives this energy from the working fluid and temperature of the working fluid is reduced as a result of this cycle. Systems in series could be installed in a direct or indirect configuration. As shown in Fig. 7, the collector serves as the evaporator in a direct series configuration and this concept is also called direct expansion. The heat transfer fluids flowing through the collectors would be, also, refrigerant of the heat pump units. In an indirect series concept, a liquid-to-liquid heat pump can be assembled as a closed unit and the heat energy from the solar collectors is conveyed to the refrigerant loop of the heat pump through the evaporator heat exchanger. Fig. 8 presents a schematic diagram of the indirect series concept.

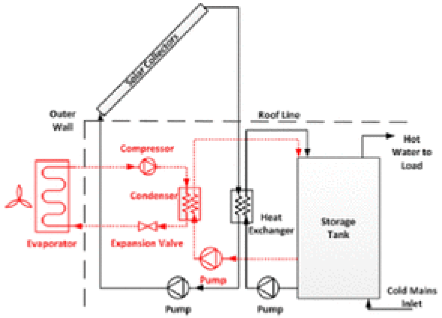

Fig. 6 Parallel type SAHP [19].

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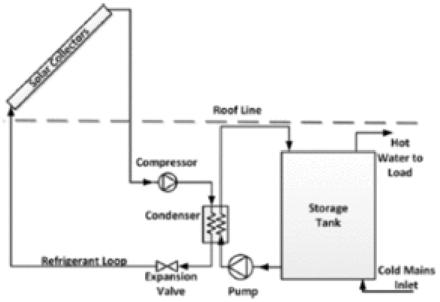

Fig. 7 Direct series type SAHP [19].

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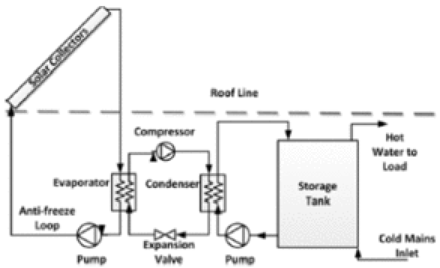

Fig. 8 Indirect series type SAHP [19].

alt-text: Fig. 8

5 Literature review

Ever since Sporn et al. [21] and Jordan et al. [22] enlightened the SAHP concept, a number of experimental studies have been conducted and published in the literature such as Morgan et al. [23], Chaturvedi et al. [24], MacArthur et al. [25] and some others have contributed to the development of this technology as well. Since 1970 s, SAHP systems have experienced considerable developments, as a reaction to the global energy concerns like energy crisis and greenhouse effect. One of the early studies on SAHP systems was carried out by Lior [27]. The focus of this study was mainly on the reduction of resource energy consumption of vapour compression heat pump by utilising solar energy. Also, Krakow and Lin [28] developed a computer model for system simulation of heat pump performance.

5.1 IEA: SHC ~~Programme~~programme Task 44

The objective of International Energy Agency (IEA)'s(IEA)'s Solar Heating and Cooling (SHC) programme Task 44 was to optimise combined solar and heat pump systems for single dwelling applications and to provide a common definition for the performance of such systems [29]. This project was performed along with the IEA Heat Pump programme denoted as Annex 38. The task mainly focused on small-scale heating and domestic hot water systems, electrically driven heat pumps etc. Task 44 also involved the assessment of solar and heat pump systems under Subtask B that aims to set common definition of performance metrics and assessment criteria as well [30].

5.2 Comparative studies of SAHP Systems

A comparative study investigates the performance characteristics of more than a SAHP system along with various components and configurations. The comparison is carried out considering experimental or simulation results in order to elicit which concept has better performance than another system. Table 2 presents an overview of the system configurations and performances from the reviewed literature. A comparative study of SAHP systems for space heating was performed by Kaygusuz et al. [31]. Each of the three configurations was examined theoretically by using the BASIC computer programprogramme and performance of the systems was compared. In the first configuration, solar assisted series heat pump system comprising conventional flat-plate water-cooled solar collectors, a heat pump unit with water-to-refrigerant heat exchanger with a phase change material (PCM) filled energy storage tank was used for space heating. In this system, the hot water from the collectors was first fed into the storage, and then was utilised in the heat pump as a heat source. The PCM storage acts as a heat source at night and cloudy days when the solar energy scarcity occurs. A schematic of the series type configuration is shown in Fig. 9. In the parallel configuration, flat-plate water-cooled solar collectors, water-to-air heat exchanger, an air cooled condenser, and a latent heat energy storage tank were the system components for space heating. This solar assisted parallel heat pump system combined a conventional solar heating system with a conventional air-to-air heat pump unit. In this system, ambient air was the heat source for the heat pump where solar energy was the heat source of the water-to-air heat exchanger and each contributes to the heating load of the building individually. A schematic of this system is presented in Fig. 10. Dual source system is the combination of the series and parallel configurations and has two evaporators allowing the heat pump to source energy either from storage tank or ambient air as shown in Fig. 11. These systems run the same way as the series system unless the storage temperature was above minimum temperature/ambient temperature, otherwise the heat pump would withdraw energy from ambient air. The overall findings of this study showed that the dual source heat pump system capitalised the ideal characteristics of the series and parallel systems and reflected it on the performance for the region where this study was conducted. Also, Free energy ratio (FER) was slightly higher than the series and parallel systems.

Table 2 Overview of comparative studies.

alt-text: Table 2

Authors	SAHP	Yield
Freeman et al. [26]	Configuration: parallel, series and dual source (liquid based) Collector specifications: flat plate	FER: 0.38-0.8 (collector area of 0–60 m^2) in Madison 0.38-0.95 (collector area of 0–60 m^2) in Albuquerque
	Storage: liquid tank	COP of HP: parallel:2.0, dual source:2.53, series:2.84 in average
	HP sink: DHW and space-heating for floor area of 120 m^2 Climate region: Madison–Wisconsin–Albuquerque, NM	Solar collector efficiency:
		Series:50%, dual source:50%, parallel:30% in January (collector area of 10 m^2)
		Series:45%, dual source:45%, parallel:35% in whole year (collector area of 10 m^2)
Kaygusuz et al. [32]	Configuration: parallel, series and dual source (liquid based) HP: hermetic type, 1490 W electrical motor driven	FER:
	Collector specifications: glazed flat plate, 18×1.62 m^2	Series:0.6, parallel:0.75, dual source:0.8
	Storage: PCM tank	SPF:
	HP sink: space-heating for floor area of 75 m^2	Series:3.3, parallel:3.37, dual source:4.2
	Climate region: Trabzon, Turkey	COP of HP:
		Series:4.0, parallel:3.0, dual source:3.5
		Solar collector efficiency:
		Series:0.56-0.64, parallel:0.48-0.54 (average monthly range)
Bertram et al.	Configuration: three different system	SPF1: 3.85 (collector area of 15 m^2)

[32]		
	Components: flat plate collectors, borehole heat exchangers and a heat pump unit	SPF2: 4.95 (collector area of 5 m^2)
	HP: 7.9 kW size	5.21 (collector area of 10 m^2)
	Storage: 300 L with solar, 150 L w/o solar	SF: 65% for DWH (collector area of 5 m^2) (SF: Solar Fraction)
	HP sink: DHW and space-heating for floor area of 140 m^2	
	Climate region: Strasbourg, France	
Haller et al. [33]	Configuration: parallel, series and dual source	This study explores when to change utilising solar energy in a parallel configuration to indirect utilisation in a heat pump. The results show that indirect utilization is advantageous when COP rise by 1 while collector efficiency boost 150% in comparison to parallel configuration
	HP: 16 kW	
	Collector specifications: covered-uncovered flat plate, 16 m^2	
	Storage: 1000 L	
	HP sink: DHW and space-heating, IEA-SHC Task 32 reference system SFH 100 building	
	Climate region: Zurich–Madrid	
Chandrashekar et al. [34]	Configuration: liquid based: parallel, series, dual-source, dual storage, air-based: parallel and dual source	In this study, the main method in assessing the performance of the systems was the Life Cycle unit cost of energy (LUC) in $/GJ. It is the ratio of the total cost over the total energy demand throughout the life cycle of the system.
	Collector specifications: flat plate	
	HP sink: DHW and space-heating for floor area of 124 m^2 of single family house & 10 story multiplex with 100 m^2 per unit	
	Climate region: Vancouver, Edmonton, Winnipeg, Toronto, Ottawa, Montreal, Fredericton	

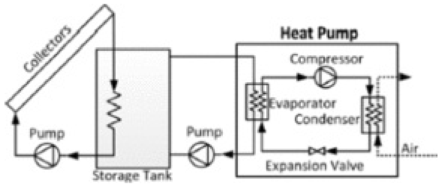

Fig. 9 Series type SAHP space-heating concept [19].

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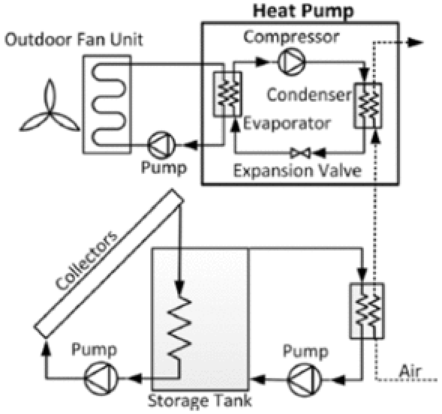

Fig. 10 Parallel type SAHP space-heating concept [19].

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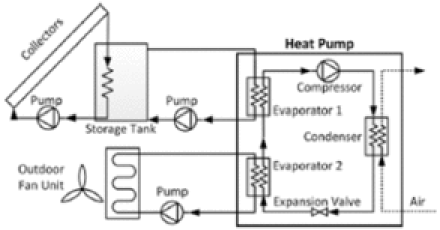

Fig. 11 Dual-source SAHP space-heating concept [19].

alt-text: Fig. 11

Bertram et al. [32] conducted a TRNSYS simulation study as part of IEA, SHC programme Task 44, to compare the performance of the three system configurations including the components of flat plate collector, borehole heat exchangers and a heat pump unit. In the system, the borehole heat exchanger was connected to act as the evaporator of the heat pump and that heat pump made the energy available to DHW and to the underfloor heating system. In the first configuration, the solar collectors charged the boreholes that introduced the energy to the heat pump. In the second configuration, the collectors were connected parallel to the heat pump to load the DHW storage directly although the heat pump still received energy from the boreholes. In the third configuration, a dual concept which was the combination of first two systems was applied. The boreholes were charged by the collectors when the load from the collectors was not sufficient enough to charge the DHW storage. According to the results, performance of the dual configuration was not any higher than the option two due to the inadequate amount of solar energy conveyed to the hot water tank. Overall findings remarked that the system performance was enhanced when solar energy loaded the storage directly rather than charging the borehole heat exchangers [32]. In another study, conducted as part of IEA, SHC programme Task 44, Haller et al. [33] introduced a mathematical relation model by using TRNSYS in order to determine if combined solar ~~collector-evaporator~~collector–evaporator of a dual ~~(solar-air)~~(solar–air) source heat pump configuration was more advantageous than utilizing solar heat directly. The examined dual configuration in this study can switch its operation between serial and parallel mode. It was shown that indirect utilization of solar heat more beneficial in terms of system performance factor when the solar radiation was under certain level depending on solar collector and heat pump characteristics. According to simulation results, using uncovered solar collectors was more advantageous in series mode and also increasing the runtime of the collectors could enhance performance of the series configuration [33].

Chandrashekar et al. [34] conducted a comparative study by using WATSON software in order to analyse six different configurations of SAHP systems including liquid and air based systems for DHW and space heating applications in seven different cities of Canada. The simulations were conducted for the six systems under prevailing climatic conditions of Vancouver and Winnipeg and the results pointed out that liquid-based systems showed better performance than air-based systems and became prominent as the best configuration with regards to unit cost of energy for a single family house in Winnipeg. However, the parallel system had come forward with the best performance in terms of energy savings in Vancouver. It was also discovered that the system performances were insensitive to the location where experimental studies took place [34].

5.3 Direct ~~Series Systems~~series systems

Chaturvedi et al. [35] developed and operated a direct series SAHP containing a bare solar collector which acted as the system evaporator. In the study, the coefficient of performance of the proposed system was monitored for various levels of solar insolation and compressor operation frequency. Test results indicated that the COP of the system was enhanced with the decreasing compressor speed as ambient temperature increases from winter to summer.

Chow, Tin Tai, Chow et al. [36] developed a mathematical model of a unitary type direct series SAHP water heating system and performed its application in subtropical Hong Kong. The water tank was the condenser of the system. Based on the dynamic simulation model, the system was found to achieve a year-long average COP of 6.46, considerably higher than its conventional counterpart. The system performed better in summer as the instantaneous COP could reach up to 10. Hawlader et al. [37] experimentally investigated a direct series SAHP water heating system. In the configuration, the tank was installed as the condenser of the system as also studied by Chow, Tin Tai, Chow et al. [36] and the refrigerant of the heat pump circulated through the coil of the heat storage tank. Also, a mathematical model was introduced in order to analyse the influence of various parameters. Fernández-Seara, José, Fernández-Seara et al. [8] experimentally studied the performance of a direct series SAHP system which also used a storage tank as the condenser like Chow, Tin Tai, Chow et al. [36] and Hawlader et al. [37]. The collectors were tested in an environment chamber under different temperatures varied from 7 °C to 22 °C while relative humidity was maintained at 55%. The tank was refilled before each test and tests were held until 55 °C of water temperature was attained. The test results indicated that as the ambient temperature increased the COP of the heat pump also increased while the time required for heating decreased. Dikici [38] experimentally tested a solar evaporator/heat pump system for domestic space heating under typical weather conditions of Elazig, Turkey. According to the results, the system COP of the SAHP was obtained as 3.08 while the exergy loss of the solar collector was found to be 1.92 kW. The second law efficiency of the compressor, condenser, evaporator and solar heat exchanger in SAHP system were evaluated 42.1%, 83.7%, 43.2% and 9.4%, respectively. The first law efficiency and exergetic efficiency of the whole system are found to be 65.6%, 30.8%, respectively.

Kuang et al. [39] presented an experimental study of a multifunctional direct series SAHP system for cooling, DHW and space heating. The collectors acted as an evaporator and water tank as a condenser in direct expansion (DX) configuration in water heating mode. However, space heating mode had slightly different configuration. The collectors served as the evaporator of the heat pump and heat was directly introduced to the space through a radiant floor. As an auxiliary heat supplier, the proposed system also comprised a forced air heat exchanger as the evaporator to assist the system when solar radiation was insufficient. In the cooling application, the collectors, as a condenser, discharged heat out in at night-time. The performance of this system was explored individually for each application. For water heating, 50 °C was attained at around an hour in a typical spring day and about 2 h required on overcast days. The system was tested 5 days for space heating in February and 2 days for cooling. The experimental results showed that the cold storage efficiency was found to be poor and cold energy stored during the night-time was insufficient to meet the cooling load.

Another study conducted by Axaopoulos et al. [40] investigated the performance of a direct series solar assisted heat pump along with a conventional thermosiphon solar system. The proposed SAHP system comprised a refrigerant filled bare solar collector as an evaporator, a heat pump unit, and a submerged heat exchanger in water storage tank as condenser. Under Athenian climate condition, COP of above 3.0 was attained and COPs between 4.0 and 5.0 was expected on a larger scale application. The SAHP system achieved to supply hot water at the desired temperature for 24 h period of the day regardless of climate conditions. Furthermore, it was deducted from the experimental results that the performance of SAHP system was more reliant on ambient temperature and wind speed, rather than on solar radiation. Ito et al. [41] also used a bare flat-plate collector as the evaporator of a HP system in a theoretical and experimental study. The results presented that 25 °C of evaporation temperature was attained when the ambient air temperature was 8 °C and the COP was monitored as 5.3. As a result of simulations, it was also found that the effect of collector area on COP of SAHPS was minor for the proposed system. Li, Y. W., Li et al. [42] and Moreno-Rodríguez, A., Moreno-Rodríguez et al. [43] conducted similar studies and obtained same promising results as well.

Xu, Guoying, Xu et al. [44] developed and numerically studied a new photovoltaic/thermal heat pump system comprising a modified collector/evaporator component which employs multi-port flat extruded aluminium tubes rather than round copper tubes used in conventional collector/evaporator systems. The results demonstrated that the proposed system achieved a 77% and 6% increase in COP and thermal efficiency, respectively. The results also suggested that the new system could heat 150 L water up 50 °C year round under both Nanjing and Hong Kong climate conditions. Table 3 presents an overview of the system components and performances from studies themed direct series SAHP systems.

Table 3 Overview of direct series systems.

alt-text: Table 3

Authors	SAHP system components	Performance
Chaturvedi et al. [35]	HP: 0.00007036 m^3/s of volumetric displacement	COP: ranging from 2.5 to 4.0
	Collector type: unglazed flat plate	
	Collector area: 3.48 m^2	
	Load: DHW	
	Climate: Norfolk, Virginia	
Chow et al. [36]	HP: 1 kW	COP:
	Collector area: 12 m^2	Max instantaneous: 10

	Collector orientation: 25°	July avg: 7.5
	Energy storage: 2500 L	January avg: 5.47
	Load: DHW	Annual avg: 6.46
	Climate: Hong Kong	
Hawlader et al. [37]	HP: variable speed compressor	SF: 0.2–0.75
	Collector type: bare flat plate	COP: 4.0–9.0
	Collector area: 3 m^2	
	Collector orientation: south 10°	
	Energy storage: 250 L	
	Load: DHW	
	Climate: Singapore	
Fernández-Seara et al. [8]	HP: rotary-type hermetic compressor	SPF: 2.11 at temperature of 7.8 °C, 3.01 at temperature of 21.9 °C
	Collector type: bare	
	Collector area: 1.6 m^2	COP: 2.44 at temperature of 7.8 °C, 3.30 at temperature of 21.9 °C
	Energy storage: 300 L	
	Load: DHW	
Kuang et al. [39]	HP: rotary type hermetic compressor x3	SPF: 2.1–3.5 for water heating, 2.1–2.7 for space heating
	Collector type: bare flat plate	
	Collector area: 10.5 m^2	
	Collector orientation: south on tilted roof	
	Energy storage: 200 L for DHW and 100 L for heat storage	
	Load: space-heating, cooling, and DHW	COP: 2.6–3.3 for space heating, 2.9 for cooling during night-time
	Climate: Shanghai, China	
Axaopoulos et al. [40]	HP: 350 W hermetic	COP: above 3.0
	Collector type: bare	4.0–5.0 expected on a larger scale
	Collector area: 3×1.4 m^2	
	Collector orientation: south with some inclination	
	Energy storage: 158 L for water storage	
	Load: DHW	
	Climate: Athens	
Ito et al. [41]	HP: 350 W	COP: 5.3 at outside temperature of 8 °C
	Collector type: bare flat plate	

	Collector area: 3.24 m^2	
	Collector orientation: south 50°	
	Load: DHW	
Li et al. [42]	HP: rotary type hermetic compressor 750 W	COP: average of 5.21
	Collector type: unglazed flat plate	
	Collector area: 4.20 m^2	
	Collector orientation: south 31.22°	
	Energy storage: 150 L for DHW	
	Load: DHW	
Moreno-Rodríguez et al. [43]	HP: 1.1 kW with R-134a	COP: min 1.7 at evaporation temperature of −8 °C and max 2.9 at evaporation temperature of 18 °C
	Collector type: bare	
	Collector area: 5.6 m^2	
	Collector orientation: south with some inclination	
	Energy storage: 300 L for DHW	
	Load: DHW	
	Climate: Madrid, Spain	
Xu et al. [44]	HP: with variable speed compressor	COP:
	Collector type: flat plate PV	Annual avg: 4.9 for Nanjing
	Collector area: 2.25 m^2	Annual avg: 5.1 for Hong Kong
	Collector orientation:	7% rise in COP
	Energy storage: 150 L	6% rise in thermal efficiency
	Load: DHW, space heating	
	Climate: Nanjing & Hong Kong, China	

5.4 Indirect ~~Series Systems~~series systems

Wang et al. [45] developed and experimentally tested a novel indirect series multifunctional system for water heating, space heating and cooling. A dual source system was designed for the space heating mode. There are two evaporators employed, one of which draws energy from the ambient air while other from a storage tank. The storage tank was charged by collectors and the heat pump unit obtained energy from the air. The same storage tank provided energy for space heating and DHW. A liquid-to-air evaporator heat exchanger was employed to cool the indoor air for space cooling mode. In this mode, the heat was transferred to the storage tank through a condenser heat exchanger as part of the heat pump operation. An electric heater was assembled to simulate solar input for the in-laboratory experimental setup. In the space heating mode, the compressor commenced to run as soon as the water temperature in tank reached 35 °C. The experimental results indicated that the efficiency could be enhanced during winter time in a region where the solar radiation was abundant. Bridgeman [46] also experimentally investigated the performance of an indirect series SAHP system in a laboratory environment for DHW. In the experimental setup, the solar heat input was simulated by an electrically heated circulation loop which supplies temperature-controlled fluid to the heat pump evaporator. Tests were performed at various evaporator supply temperatures, ranging from 10 to 30 °C. The test results showed that COP values varying between 2.8 and 3.3 depending on the evaporator and condenser temperatures.

Alkhamis et al. [47] conducted a feasibility study of an indirect solar assisted heating/cooling system for an aquatic centre for hot and humid climates. The heating was achieved by hot water obtained via heat exchange with the solar collector working fluid. Two thermal storage tanks were employed for DHW. In another study similar to Alkhamis et al. [47], the feasibility study of an indirect SAHP system for DHW was modelled in TRNSYS software and compared to conventional and electrical DHW systems by

Sterling et al. [48]. The indirect SAHP, conventional and electrical direct water heating systems were both modelled under the prevailing climatic conditions of Ottawa, Ontario. According to the simulation results, the dual tank indirect SAHP system proved to be the most energy efficient among others. It was also emphasised that the weather, depending on the geographical location, would have an ultimate impact on the performance and size of the system.

Loose et al. [49] performed field tests of various combined SAHP systems with different heat sources and presented results, as part of IEA, SHC Programmeprogramme Task 44. The system employed collectors and geothermal heat pump with borehole heat exchangers to provide DHW and space-heating to a new structure with radiant floor heating system. The collectors fed the storage directly when the sufficient solar radiation was available. Otherwise, low grade energy from the collectors would be used in the heat pump for space heating. In case of reaching energy storage capacity in the tank and the heat pump operation was inactivated; the collectors would feed the borehole heat exchanger. So, the heat pump would draw the stored energy from the boreholes after summer time. This configuration was monitored for three years and the promising results were obtained. The solar regeneration of ground boreholes ensured that the HP system could run with a high rate of seasonal performance factor (SPF) in a long term.

Bakirci et al. [50] investigated the performance characteristics of an indirect SAHP system for space heating. The collectors directly charged a storage tank which was linked to an evaporator to provide a heat source for the heat pump. The ultimate heat was introduced to the space through a radiator. Zhang et al. [51] developed and test a novel solar photovoltaic/loop-heat-pipe HP system for space heating or DHW. The solar heat was exchanged through a flat-plate heat exchanger acting as the condenser of the heat pipe loop and the evaporator of the heat pump cycle. The average values of COP for both thermal and PV/T were found to be 5.51 and 8.71 under the prevailing climatic conditions of Shanghai, China. The result proved that proposed system had a potential of achieving enhanced solar thermal efficiencies around 1.5–4 times more than conventional counterparts. In another study, Shilin et al. [52] proposed and experimentally studied an indirect-expansion SAHP radiant floor space heating system in Beijing, China. The configuration of the system varied as solar alone, solar with water-source heat pump and water source heat pump alone depending on the solar collector’s outlet temperature.

Bai et al. [53] theoretically analysed an indirect combined hybrid PV/T SAHP system for DHW. The system was modelled with TRNSYS computation environment and year round performance results were simulated under the subtropical climatic conditions of Hong Kong and multiple climates in France. The results proved that COP of 4.1 under the subtropical climate of Hong Kong was attained and also, 67% of high fractional energy saving ratio was accomplished in comparison with a conventional heating system. Table 4 presents an overview of the system components and performances from studies themed indirect series SAHP systems.

Table 4 Overview of indirect series systems.

alt-text: Table 4

Authors	SAHP system components	Performance
Wang et al. [45]	HP: hermetic rotary compressor with the displacement volume of 22.5 m^3	COP: 4.0 for heating
	Energy storage: 150 L	
	Load: DHW, space heating, and cooling	
Bridgeman [46]	HP: 617 W	COP: 2.8–3.3 depending on the evaporator and condenser temperatures
	Collector type: 3500 W electric heater for solar heat input, unglazed solar collectors for simulation	
	Collector orientation: south, 10–80° for simulation	
	Energy storage: 270 L for experiment	
	Load: DHW	
	Climate: Toronto, Vancouver, Montreal, Halifax and Winnipeg	
Alkhamis et al. [47]	Collector area: 600–1200 m^2 (simulation)	SD (solar displacement): 25%
	Energy storage: 11.36 m^3	
	Load: DHW (pool area of 1172 m^2)	
	Climate: Miami, Florida	
Sterling et al. [48]	HP: Type668 (simulation)	COP: 2.5–5.0
	Collector type: flat plate	
	Collector area: 4 m^2	

	Collector orientation: south, 45°	
	Load: DHW	
	Climate: Ottawa, Ontario, Canada	
Loose et al. [49]	HP: 5 kW integrated with 75 m borehole heat exchanger	SPF: More than 5
	Collector area: 11 m^2	
	Energy storage: 750 L	
	Load: DHW and space heating (140 m^2 of floor area)	
	Climate: Herford, Germany	
Bakirci et al. [50]	HP: compressor driven by 1491 W motor	SPF: 2.5–2.9
	Collector area: 12×1.64 m^2	COP: 3.3–3.8
	Collector orientation: south, 50°	
	Energy storage: 2000 L	
	Load: space heating (175 m^2 of floor area)	
	Climate: Erzurum, Turkey	
Zhang et al. [51]	HP: 0.75 kW	COP:
	Collector type: PV/loop heat pipe	Thermal: 5.51
	Collector area: 0.612 m^2	PV/T: 8.71 (1.5–4 times more than conventional ones)
	Collector orientation: 30°	
	Energy storage: 35 L	
	Load: space heating or DHW	
	Climate: Shanghai, China	
Shilin et al. [52]	HP: 3 kW electrical heater	COP: ns
	Collector type: heat pipe vacuum tube	
	Collector area: 17.5 m^2	
	Energy storage: 1000 L	
	Load: space heating (50 m^2 of floor area)	
	Climate: Beijing, China	
Bai et al. [53]	HP: 14.61 kW	COP: Mean of 4.9
	Collector type: PV/T	
	Collector area: 600 m^2	
	Collector orientation: south, 23°	

	Energy storage: 60 m^3	
	Load: DHW	
	Climate: Hong Kong, Paris, Lyon, Nice	

6 Design components

6.1 SAHP components and investigated parameters

The long term performance of a SAHP system entirely depends on the size and configuration of the components that must meet the demands for load and the daily radiation at a given location [55]. In this manner, a SAHP system comprises four main components which are ~~collector-evaporator~~collector–evaporator (combined in direct series types), compressor, thermal expansion valves and the storage-heat exchanging tank. The studies conducted on SAP systems show that collector (also evaporator for direct series type SAHP systems), and the compressor are the components that are mainly effected by the amount of heat obtained from the heat source. Also, compressor and pumps are the power consuming devices in a SAHP system.

7 ~~Collector-evaporator~~Collector–evaporator

Glazed and unglazed flat plate solar collectors are the two major collector types mostly used in SAHP system applications that research has focused on. Both of them have been widely used in the research work for SAHP systems as briefly shown in Table 5. It is obvious that unglazed flat plate collector is the most widely employed and investigated one among the two types [56]. This is mainly owing to encouraging collector efficiencies. Having unglazed collector (also means no cover), heat loss is prevented so that available heat is fully absorbed by the plate and transferred to the low temperature flowing fluid. This key advantage of uncovered flat plate solar collectors has been cited in numerous research studies of SAHP system applications [57].

Table 5 various component types and parameters investigated in reviewed studies

alt-text: Table 5

Components	Type	Investigated parameter	References
Collector (Evaporator)	Glazed	Collector area, efficiency, performance data, refrigerant evaporation, water temperature, weather conditions	[13,14,15,16,31,47,49,65,66,67]
	Unglazed	Collector design, efficiency, area, wind speed, load temperature, refrigerant water temperature and weather conditions	[3,8,9,11,15,35,36,38,40,41,42,45,53,55,56,58,59,60,61,63]
	PV module	Temperature, power efficiency and output, solar radiation, wind velocity, heat gain	[17,43,50,52,57,63]
	Vacuum tube	Climate conditions, module, temperature, mass flow rate, water temperature	[12, 63]
Compressor	Reciprocating hermetic	Compressor speed, power input, compressor heating capacity, operation mode, fuel depletion ratio, power consumption, performance rate, heating capacity, compressor temperature, irreversibility rate	[11,36,42,45,49,56,59,60]
	Rotary hermetic	Material, mass flow rate, power, pressure drop	[8,13,31,39,40,44,53,55,61]
	Variable frequency reciprocating	Compressor speed, mass flow rate, power input, pressure drop	[12,17,35,38,41,43,57]
Condenser	Water tank	Heat transfer rate, heat pump capacity, energy storage and efficiency, storage volume	[8,11,12,13,16,35,36,38,39,40,41,42,43,44,45,49,50,51,53,55,56,57,61,65,69]
	Air	Ambient conditions, heating capacity, pressure	[7,9,10,17,31,58,60]
Expansion valve	Thermostatic	Exergetic performance, mass flow rate	[9,11,17,35,38,39,40,41,42,45,53,55,59,60,61,65]
	Capillary tube	ns	[43,58]

Other types of solar collectors including the vacuum tube, photovoltaic/thermal and evacuated tubes modules have also been investigated in tandem with heat pump systems to form SAHP systems. These modules also yielded high temperature difference and found to be worth to assemble at the heat source side of SAPHs. ~~Ji, Jie,~~ Ji et al. [17] investigated the performance of the photovoltaic modules with heat pump units under prevailing weather conditions of Hefei in Central China and obtained COP of up to 10.4 for the overall PV-SAHP system.

Reduction of heat losses through various designs has largely been practised in determination of system performance. In those practices, certain factors determining the system performance such as size and material of the collectors, pipe size and dimensions, fluid properties, wind velocity, weather conditions and solar radiation etc. have been analysed pertaining to the heat source unit. Among these parameters, the ambient temperature and solar radiation are the most influencing factors but their instability is a major concern [5]. Vacuum tube heat pipe collector system was studied by Shilin et al. [52] to propose a likely solution of instability and intermittence of solar heating systems. With respect to the analyses, a control scheme and operation suggestion was provided.

8 Compressor

Efficiency and speed are two significant decisive factors for compressor units used in SAHP systems as these factors are related with refrigerant pressure and heating temperature rise. However, considering compressors below their capacities is a real issue if the required output temperature is not delivered or the delivery is too high. This mismatch between compressor speed and instability of the available solar radiation has, in many studies, been found to be highly influential on the performance of the compressor. It is shown in literature reviews that a better compressor performance is achievable by employing variable speed compressors. Kuang et al. [39] achieved a COP range between 2.6 and 3.3 in the SAHP configuration using a variable speed compressor. Another study revealed that employing variable frequency compressor in a SAHP system resulted in higher COPs and also getting high solar radiation rate yielded enhanced heat gain in condenser [35].

It is advised that setting the compressor speed at a low rate will not only enhance COP but also extend the life cycle of the compressor. Huang et al. [12] found that COP decreased from 2.82 to 1.86 with increasing compressor speed. Also, Guoying et al. [44] results indicated that decreasing compressor speed from 5000 r/min to 1500 r/min resulted in significant improvement in system COP from 5.89 to 7.36 in Nanjing and from 5.59 to 7.09 in Hong Kong. Besides COP, another advantage of setting the compressor at a low speed is the possibility of reducing the compressor energy consumption which will also lead to enhanced COPs.

9 Condenser

For SAHP low temperature water heating applications, the condensers mostly function both as heat exchanger and heat storage tank and copper tube piping has been found to be extensively used for refrigerant flow and heat exchange with the cold water in the tank. Hawlader et al. [37] conducted an investigation on fibre glass made water condensing tank. Condenser performance primarily depends on the reduction of heat loss through radiation so that its design plays a key role towards enhanced performance characteristics. Thus, numerous studies have been concerned with design parameters in relation with other system components. Chow et al. [36] reported on numerical modelling of a SAHP water heating system that compressor speed could have a strong effect on the condenser heat gain. Moreover, condensing refrigerant properties namely heat transfer coefficient, water and ambient temperature are the factors that should be considered in condenser design and performance. Stratification effect in water tank is also crucial if energy is stored in a water tank for future use. Anderson et al. [54] experimentally indicated that extended area of the condenser in connection with the water tank enhanced overall performance of the system.

10 Expansion valve and pump

An expansion valve regulates the pressure and flow rate of the refrigerant in a heat pump cycle. It has various types according to its functions which shown to be highly effective on the performance of compressor and mass flow rate of the working fluid. Besides widely used thermostatic one, electronic type has also been used in SAHP systems [5]. The electronic expansion valve with a controller and a variable speed compressor are recommended to be employed in a SAHP system in order to sustain a high system performance, system reliability and a proper match between solar collector and compressor units [42].

11 Types of refrigerant used in SAHP Systems

An effective working fluid for SAHP systems must have a high thermal conductivity, critical temperature and evaporation enthalpy to attain high heat transfer rate and COP. The refrigerant must also possess qualities like very low freezing point, specific volume capacity and viscosity to conform to heat pump operation and reduce power consumption. Ozone layer depletion and climate change are two main refrigerant related concerns that should be considered in their selection criteria. In SAHP systems, there are two types of refrigerants in use namely plain and mixed refrigerants. Especially mixed refrigerants have been considered lately for SAHP systems with the need of environmentally friendly, safe and effective refrigerants. Gorozabel et al. [71] replaced R12 with R134 and compared the system performance. ~~2-4%~~2–4% degradation in system performance for collector temperature range of ~~0-20~~0–20 °C was reported. Also, a comparison between different refrigerants was conducted and shown that R12 yielded the highest COP followed by R22, R134A, R410A, and R407C/R404A, respectively. Mohanraj et al. [72] presented a comparison study between R22 and a mixture of R407C for a SAHP system. The energy performance ratio (EPR) of mixture was found to be ~~2-5%~~2–5% lower compared to R22. However, total equivalent warming impact of the mixture was reported to be lower compared to R22 under leakage conditions. Although the performance of the mixture type refrigerants was found to be still lower than that of conventional primary refrigerants, promising results showed the high potential of mixture over others.

12 Thermal performance characteristics of SAHP

An in-depth comprehension overview and awareness of the presence of interdependent parameters and their interaction is essential to anticipate the thermal performance in designing stage of any SAHP system. Therefore, from both experimental and theoretical studies conducted to investigate the thermal characteristics of various type SAHP systems, a number of findings have been introduced about thermal performance classifications and the influencing parameters based on the analysis performed. Thermal performance analyses types, in this study, have been categorised as coefficient of performance (COP), energy and exergy ~~analyses.~~analyses. Table 6 provides a list of the thermal performance analyses of SAHP systems reviewed, findings and evaluation methods, respectively.

Table 6 Overview of some SAHP studies with thermal performance analyses and evaluation methods.

alt-text: Table 6

Refs.	Study type	Analysis	Result	Performance evaluation
[52]	Numerical	COP	4.1	Function of climate conditions, collector specifications, and size of heating area
[53]	Experimental	COP	6 & 4.5	Function of climate conditions, heat transfer and power to time required for the heating cycle
[54]	Numerical	COP	3–4 & 8–9	Function of time
[55]	Analytical and Experimental	COP	6.4	Function of climate conditions, collector area, storage volume and compressor speed
[58]	Theoretical and Experimental	COP	1.7–2.5	Function of outlet temperature with respect to various solar insolation values
[41]	Experimental	Exergy	10–30%	Function of time for useful heat gain
[42]	Theoretical and Experimental	COP	1.7 & 2.9	Function of evaporation temperature, heat and compressor power
[57]	Experimental	COP	9.5 & 6.3	Function of condensing temperature, PV efficiency, compressor frequency and time
[58]	Theoretical and Experimental	Exergy	ns	Function of climate conditions, temperature difference and time
[59]	Review and Experimental	Exergy	ns	Function of fuel consumption and heat delivery
[60]	Theoretical and Experimental	Exergy	0.26%	Efficiency and losses

13 Coefficient of performance (COP)

Coefficient of the performance (COP) is the fundamental and predominant performance evaluation approach for SAHP Systems. It is defined as the ratio of heating or cooling effect Q_{sys}~~sys~~, to the total work input W_{sys}~~sys~~. This description is valid for any heat pump either stand-alone or combined with refrigeration cycles and is mathematically stated as

$$\mathrm{COP}_{sys} = \frac{Q_{SYS}}{W_{SYS}} \tag{1}$$

Eq. 1 can be further expressed for direct series SAHP (DX-SAHP) systems as [5]

$$\mathrm{COP}_{sys} = \frac{m_f c_f \Delta TH_{h,c}}{(W_{comp} + W_{pump} + W_{valve})_{h,c}} \tag{2}$$

Eq. 2 shows that heating or cooling effect of the system is a function of the fluid mass flow rate, *m*, specific heat capacity, *c*, and the temperature difference, ΔT. The subscripts, h and c, stand for heating or cooling state, respectively. Total work input is also a function of the sum of the work input to system components.

Eq. 1 can be also extended for indirect series SAHP systems as [50]

$$\mathrm{COP}_{sys} = \frac{\dot{m}_{con} c_w (T_{cwo} - T_{ewi})}{\dot{W}_{comp} + W_{\Sigma p}} \tag{3}$$

Here, the performance of an indirect series SAHP system is likewise a function of mass flow rate, specific heat capacity and the temperature difference across the system. The subscripts, con, w, cwo, ewi, comp and p represent condenser, condenser water outlet, plate heat exchanger water inlet, compressor and circulation pump, respectively. Other versions of expressing COP also exist for various SAHP configurations. Another form of COP evaluation known as seasonal coefficient of performance (SCP) is the time and season of SAHP applications and is obtained by periodical computation of regular COP for a particular season or time frame.

The effectiveness of a SAHP system, COP, entirely bounds up with solar radiation and ambient air temperature. These factors ultimately determine how high the heat generated at the evaporator and the evaporator temperature is considered in evaluation of the entire SAHP system effectiveness. Ito et al. [41] stated the significant contribution of the solar radiation to the evaporation temperatures and COP as well. Further, COP and efficiency increase as ambient temperature rises where COP increases and efficiency drops with the increasing solar radiation level [62].

14 Energy-exergyEnergy–exergy efficiency

Energy and exergy analysis has attracted considerable interest as it evaluates the performance of a system׳s components individually. This information allows researchers take preventive actions and necessary improvements to be implemented on that component [5]. The energy efficiency of a system can be described as the ratio of the sum of heat delivered by working fluid, Q_{c-d}, and heat delivered by stored fluid, Q_{D-st}, for a time range over the sum of heat supplied to working fluid, Q_{sp-sp}, and the stored heat from the energy input, Q_{sp-i}.

Q_{c-d} and Q_{D-st} are both a function of the m-p, c_p, and ΔT as a kinetic state of working fluid. Moreover, Q_{sp-sp} is a function of the heat transfer, measured solar radiation and ambient temperature over a time frame. Q_{sp-i} is a function of the energy input to convey heat to/from the working fluid and storage. All functions are mathematically defined in an energy equation as

$$\eta_{sys} = Q_{gain}/Q_{in} = \frac{Q_d + Q_{d-st}}{Q_{sp} + Q_{sp-i}} \tag{4}$$

In exergy analysis, general form of energy balance equation (Eq. 5) is used to define the efficiency and losses. The only difference is the identification of losses accounted for an exergy analysis either of a component or an entire system. The loss is introduced by the second term on the right hand side of Eq. 6.

$$\sum \dot{E}_{in} = \sum \dot{E}_{out} \tag{5}$$

$$\sum \dot{E}x_{in} = \sum \dot{E}x_{out} + \sum \dot{E}x_{loss} \tag{6}$$

So the exergy efficiency is the ratio of the total exergy gain to the total exergy input. As defined in Eqs. 7 and 8, m is the working fluid mass flow rate, h is the specific enthalpy, s is the specific entropy, T is the temperature and 0 represents the initial state of the refrigerant.

$$\dot{E}x_{gain} = m[(h - h_0) - T_0(s - s_0)] \tag{7}$$

$$\eta_{sys} = \dot{E}x_{gain}/\dot{E}x_{in} \tag{8}$$

The exergy performance analysis describes the useful heat gain by a system and generally referred to heating capacity in regular heat pump systems [5]. This analysis is capable of describing effects of both solar radiation and ambient temperature on a SAHP system. According to [58,59,63], they have been able to produce valuable outcomes by improving SAHP system performance via exergy analysis as the performance heavily relies on factors such as wind speed, collector size, compressor speed, time and other arrangements. Saidur et al. [64] reviewed the effects of solar and ambient temperature in various types of SAHP systems and concluded that the highest exergy destruction was attained in solar collectors in most of the solar assisted heat pump systems on the exergy efficiency performance. Other research also revealed that solar radiation level and ambient temperature had a certain effect on the exergy performance of the system [65,–68] [67] [68]. Some researchers reported the exergy efficiency of the whole system [42,61,65] while others evaluated and reported the exergy performance of the individual components separately [41,42,60]. Lastly, a few carried out the exergy analysis both for individual components and overall system [42,61], and [65]. One can conclude that the exergy efficiencies declared have not tracked the same assessment pattern thereby, needing much effort to embrace clear absolute order of size, figures or performance range in common for the exergy efficiency. As shown in Table 6, exergetic efficiency of different SAHP systems were attained as a function of various parameters. In Table 6, the highest obtained exergy efficiencyefficiency was 30% by Li, Y. W., Li et al. [42] while the lowest was noted as 0.26% by Mohanraj et al. [61]. Wind velocity along with the solar radiation was another major parameter to be considered in exergetic analyses of SAHP systems. As the wind speed increased, heat loss at the solar collectors also increased and this would ultimately result in degradation in exergy differencedifference at the condenser [5]. Table 6

An important benefit of the exergy analysis is that efficiency improvements and reductions in thermodynamic losses attributable to more sustainable technologies are clearly identified by exergy [69]. So several researchers followed the same pattern and identified system characteristics by exergy analysis in design process of SAHP systems. Liu et al. [70] identified the greatest irreversibility occurrence at the compressor through energy-exergyenergy–exergy analysis. Li et al. [42] reported the highest exergy loss occurrence in the collector for small size SAHP systems and at the compressor for large size in their study.

15 Discussion

A wide range of SAHP system configurations and systematic description were presented in a unified visualisation scheme called “square view”. This approach mainly simplified the steps to describe and classify combined solar thermal and heat pump systems, and visualise such systems systematically. With this approach, a basis was provided also to compare the combined solar thermal and heat pump systems. Thereby, the comparative studies were carried out on parallel, series and dual source systems showing that performance of the various configurations mainly depended on number of elements including resident behaviour, procedure parameters, building features, system components and climatic conditions. However, it was recognised that various performance criteria was applied and this incoherence complicated the possibility of performing a proper comparison among the broad range of system studies. Therefore, a set of standardised performance criteria would facilitate the analysis and comparison of different SAHP systems. In this regard, Task 44 Subtask B intends to achieve a common method for the assessment of these systems and this work is still under progress [19]. On entire SAHP systems, energy sources and total energy load should be clarified for the assessment of those systems as these parameters may vary with components employed in the system, building loads and climate. For this reason, parameters like free energy ratio (FER) or seasonal performance factor (SPF) should also be considered on the entire system. Although the individual performance of the components is also significant, performance evaluations of solar collectors and heat pump do not merely picture the power need to meet the loads [73].

It was also noted that variety of configurations, types and factors make it challenging to examine a particular system, match with the others and design it for a specific climate [74]. In this study, key system parameters and performance assessment from a number of previous studies were presented. One should note that a proper comparison of systems should match the similar systems with the same components, bonded to same energy source and total energy loads [75]. Although this method was applied to each comparative study, the conclusions among the studies were subjected to be unlike as energy source and load differed. For this reason, it is not that simple to compare the individual series systems since there must be a common set of methods for a proper comparison.

15.1 Future directions in SAHP research and development

Utilisation of solar energy as a free and renewable energy source is the way forward in research and development of SAHP. It has various advantages including low carbon emission, utilisation of waste heat, raising the temperature significantly by compression and versatility for variety of applications.

Having a look into the future trends of SAHP technologies, it is likely to recognise growing demands for improved energy efficiency, reduced impact on environment, and better utilisation of renewable energy sources at lower total cost. Recently, the major motive for innovation in SAHP technologies is to utilise low grade solar thermal energy in efficient and effective way. This goal can only be accomplished in several ways to produce a renewable heat source for heat pump technologies [76].

Solar collectors are the most important components in SAHP systems. As innovation is key in the design of solar collectors that both air and water based collectors can be used, performance of these solar collectors should be substantially improved in order to get acceptance for most of the commercial applications [77]. These require considerable amount of research carrying investigations on the performance of the different types of solar and PV/T water based collectors, glass covered, selective surfaces, and COPs of the SAHP systems [78].

Solar energy systems are essentially implemented today to reduce tomorrow′s fuel bill. It can be easily concluded from the techno-economic analysis of individual SAHP systems that the economic payback period of these systems have been remarkably decreased. Therefore, much attentions is also needed to prove economic aspects of SAHP systems [79].

15.2 Energy ~~Codes~~codes & ~~Standards~~standards

Application of solar assisted heat pumps are subject to building and facility energy codes and standards. In addition, the equipment employed is also subject to commercial equipment energy codes and standards. In the UK, the Microgeneration Installation Standard: MIS 3005 Requirements for Contractors Undertaking the Supply, Design, Installation, Set to Work Commissioning and Handover of Microgeneration Heat Pump Systems simply addresses six key areas: heat loss calculation (including power & energy), heat pump sizing, heat emitter selection, domestic hot water preparation, cost calculations and collector design and installation. Since publication of MIS 3005, there have been updates on standards such as BS EN 12831 National Annex and CIBSE Domestic Heating Design Guides. These energy regulations that impact facilities are specifically BS EN 12831:2003: Heating systems in buildings. Equipment efficiency standards, as complementary guidance to BS EN 806, is EN 8558:2011: Guide to the design, installation, testing and maintenance of services supplying water for domestic use within buildings and their curtilages. There are also standards and regulations for solar thermal collectors which are the most important components in SAHP systems. Microgeneration Installation Standard: MIS 3001, BS5918: 1989 Code of practice for solar heating systems for domestic hot water, BS EN 12975: 2006 Thermal solar systems and components, are some of the approved codes and standards for solar thermal collectors. Furthermore, CIBSE's 'Solar Heating Design and Installation Guide' and 'Knowledge Series 15 – Capturing solar energy', ASHRAE's 'Systems Handbook: Solar Energy Equipment' and 'Applications Handbook: Solar Energy Use' in related chapters are some of the excellent resources for detailed insight into solar collectors and system design [80].

International codes and standards for solar assisted heat pumps exist relatively widely. There are also comprehensive, consistent set of technical standards for solar assisted heat pump components across Europe, through EN standards for testing and safety etc., which European Member states have adopted into national standardisation or alternatively replaced pre-existing national standards with the EN standards [81].

Conclusion

In the current study, a number of past and current works on solar assisted heat pump (SAHP) systems for low temperature water heating applications has been presented. Also, various studies from International Energy Agency's Task 44 of the Solar Heating and Cooling Programme investigating solar heat pump systems have been provided. A central challenge in the classification of various SAHP systems is to having a variety of configurations, parameters and performance criteria that increase the level of complexity to compare and analyse the studies of different systems. So that the final classification objective is met through adopting the visualisation approach first introduced by Elimar et al. [6].

Reviewed studies indicate that the effect of solar heat energy on the performance of both collector and heat pump individually, and on the entire SAHP system to be majorly significant. Then again, the advanced configuration types of SAHP systems were found to be performing better than the conventional basic types with reference to reported COPs that might draw considerable interest for further investigations.

Referring to the works of various researchers, a single optimum SAHP system configuration cannot be identified as the configuration may vary with size of the residential area, load and climatic conditions. Likewise, future studies must apply a common standardised assessment method for the performance evaluations of SAHP systems. Overall, the studies imply that combined solar thermal and heat pump technology has the potential of providing an effective alternative for different climates with adjustable configurations.

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