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REVIEW OF THE RECENT ADVANCES IN SOLAR ASSISTED HEAT PUMPS INTEGRATED WITH RENEWABLE ENERGY SOURCES

Filipe Nogueira de Carvalho
Federal University of Minas Gerais (UFMG), Post-Graduate Program in Mechanical Engineering, Av. Antônio Carlos, 6627, Belo Horizonte (MG), 31270-901, Brazil
filipenc@ufmg.br;

Willian Moreira Duarte
Luiz Machado
Federal University of Minas Gerais (UFMG), Department of Mechanical Engineering, Av. Antônio Carlos, 6627, Belo Horizonte - MG, 31270-901, Brazil
luizm@demec.ufmg.br; willianmoreira@ufmg.br;

Abstract. *This review article aims to investigate the arrangements, energy performance, economic viability and environmental impacts of solar assisted heat pumps (SAHP) integrated with renewable energy sources. Such equipments have been the object of recent studies in the area of energy and sustainability as it involves the conversion of solar energy into thermal energy to promote direct heating of water, space, drying, desalination and also expansion of the refrigerant fluid in the evaporator of the equipment. In addition it is also responsible for the conversion of photovoltaic energy to generate electric current to supply the compressor power demand when combined with photovoltaic panels.*
The renewable source energy production strategy to enhance the heat pump performance is a promising technology to fulfill the Net Zero Scenario. Furthermore, the increasing sales year after year demonstrate that SAHPs are able to completely overcome the heat demand provided by boilers that consume fossil fuels and contribute to accelerate the ozone layer depletion. The information presented in this article contribute with other researches and professionals interested in the SAHP and renewable energy sources technology.

Keywords: *Solar assisted heat pump, solar evaporator, photovoltaic panels, thermal energy*

1. INTRODUCTION

According to the European Commission (2020), buildings are responsible for about 40% of the Europe Union energy consumption and 36% of greenhouse gas emissions from energy. But only 1% of buildings undergo energy efficient renovation every year, so effective action is crucial to making Europe climate-neutral by 2050. One of the intended strategies to reduce those emissions is the decarbonisation of heating and cooling.

The International Energy Agency (2022), reported that the market of heating energy is slowly transitioning from a fossil fuel-dominated technology mix towards more efficient or lower-carbon solutions. After years of slow but steady decline, the share of coal, oil and natural gas boilers in global heating equipment sales fell under 50% in 2020. Globally solar thermal technology met less than 3% of space and water heating demand in the same year and 180 million heat pumps in heating mode were in operation, up from under 100 million in 2010. These equipments still meet no more than 7% of global heating needs in buildings. To be in line with the Net Zero Scenario, however, 600 million heat pumps need to provide 20% of global heat demand for buildings by 2030, according to IEA (2019).

The integration of heat pump with solar energy source is classified as solar assisted heat pump (SAHP). Badiei et al. (2020), stated that by modifying the system configuration, reduced cost and improved efficiencies can be achieved, resulting in increasing interest in hybrid systems with a variety of system configurations suitable to various climates. There have been several studies on how SAHPs can supply the heat demand on drying, water heating, space heating and desalination systems (Mohanraj et al., 2018a,b). Recently Duarte et al. (2021) developed a theoretical work to compare the production of hot water in hot climates and found that the SAHP presented the best payback among the studied systems.

The following aspects related to the SAHPs will be presented:

- Types of configuration;
- The energy and performance mathematical formulation;
- The economical aspects and payback calculation;

2. CONFIGURATION OF SAHP

The SAHPs are classified in literature according to Cai et al. (2019), into two types: (i) direct expansion type (DX-SAHP) and (ii) indirect expansion type (IX-SAHP). Solar radiation is direct absorbed in solar collector/evaporator in the DX-SAHP (Fig. 1 a), while in the IX-SAHP (Fig. 1 b) solar radiation is harvested in the solar collector and transfers heat to the evaporator.

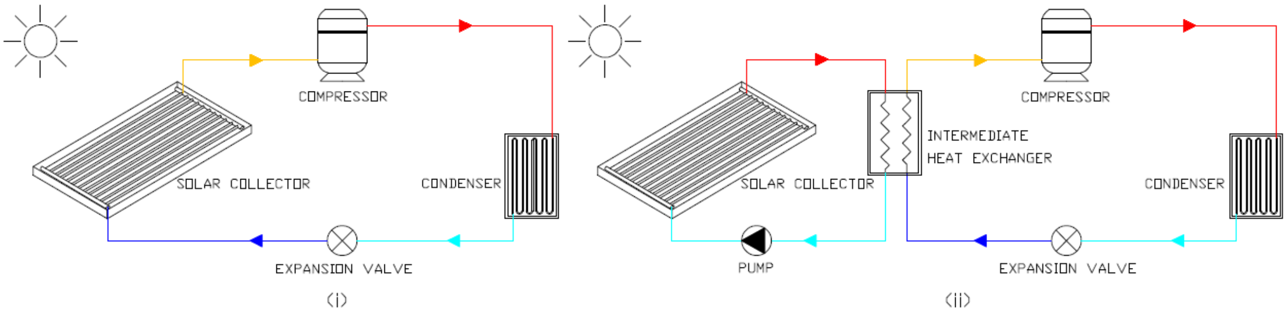

Figure 1. Schematic view of (i) DX-SAHP and (ii) IX-SAHP.

In SAHP the solar energy is classified as the heat source, that is transferred through the expansion of a refrigerant to the heat sink (Omojaro and Breitkopf, 2013) that can be a reservoir to provide domestic heat water, a radiant floor, and also in industrial applications such as water desalinization and in grain drying. According to the heat source another typical classification is also used by the scientific community (Mohanraj et al., 2018a): (iii) air source heat pump (ASHP) in which the heat to evaporate the refrigerant in the evaporator is provided by the ambient air, (iv) solar geothermal hybrid source heat pump (SGHSHP) in which the heat to evaporate the refrigerant in the evaporator is provided by the solar radiation and geothermal source that can be configured in series or parallel arrangement, (v) photovoltaic thermal solar assisted heat pump (PVT-SAHP) in which the heat to evaporate the refrigerant in the evaporator is provided by the solar radiation and a photovoltaic layer of panels that are coupled to the top of the solar collector to provide electric energy to the compressor or to the grid. Different configuration using wind energy and also combining two or more renewable energy sources are seen in literature but accounting with less related studies.

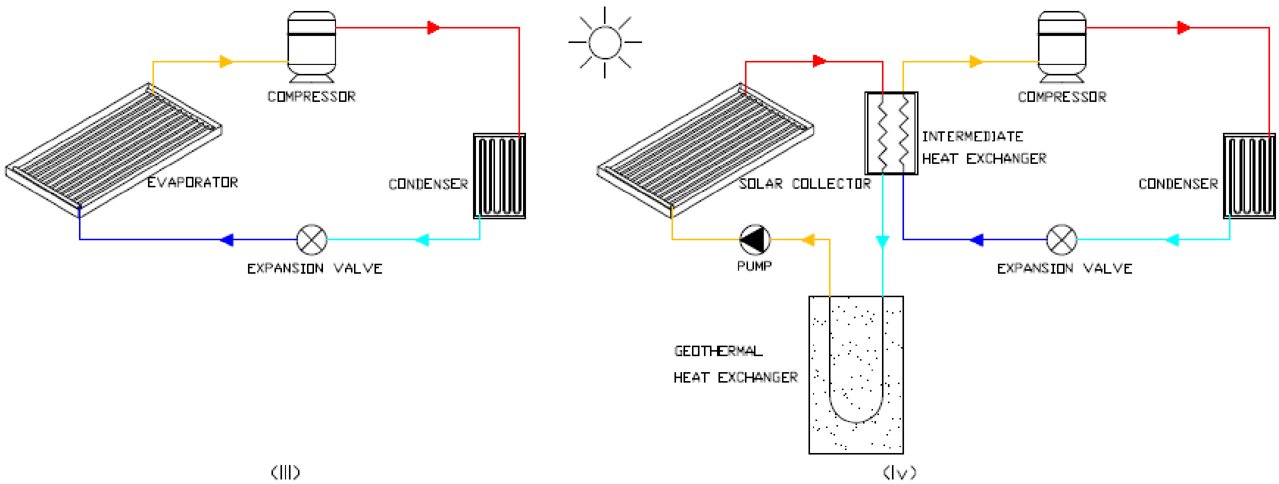

Figure 2. Schematic view of (iii) ASHP and (iv) SGHSHP.

The last researches and main results about the different SAHP systems configurations will be presented in the following sections.

2.1 DX-SAHP

Recently Dai et al. (2022), developed a theoretical work to evaluate the feasibility to replace a conventional ambient air vaporizer of liquefied natural gas for a DX-SAHP in China. Comparing with the conventional ambient air vaporizer (AAV), the two-phase length of AAV in the DX-SAHP system was reduced by 12.7% and 20.2% on the typical winter and summer day, while the outlet liquefied natural gas vaporization (LNV) temperature was improved by 5.33 K and 11.56 K. The authors concluded that proposed system may provide a new perspective for the AAV defrosting and LNG vaporization optimization. In another study Sivakumar et al. (2022), investigated in an experimental and theoretical research a DX-SAHP for space heating in India employing a new concept of solar evaporator-collector called packed bed and found that the pay-back duration resulted in 9.9 months with 70.4% reduced CO_2 emissions compared to electrical resistance heaters for the twenty years lifetime. The system schematic diagram and experimental apparatus is depicted in Fig. 3.

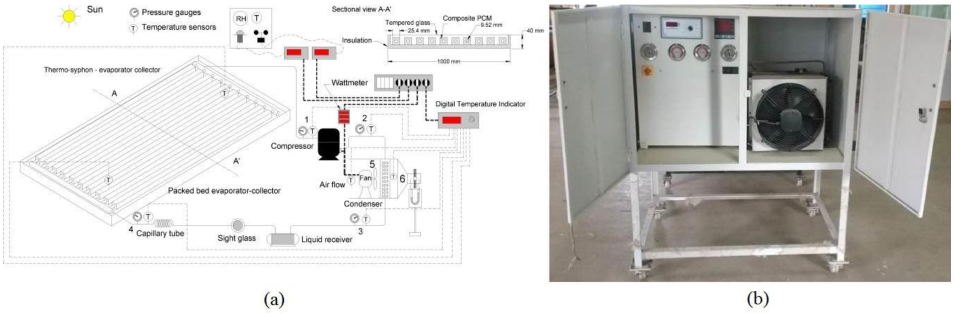

Figure 3. Schematic view of (a) DX-SAHP and (b) experimental apparatus (Sivakumar et al., 2022)

2.2 IX-SAHP

A theoretical study about IX-SAHP in a cascaded configuration for space heating supply in a district region of Germany showed that among the range of refrigerants applied to the heat pump the most suitable was the R1234ze that exhibited the best combination of thermodynamic, environmental and safety properties (Xiao et al., 2022). In a recent article by Tomar et. al (2022), a theoretical and experimental investigation on IX-SAHP enhanced by photovoltaic heat pipe technology for water heating in Honk Kong as depicted in Fig. 4 stated that the overall thermal efficiency and overall electrical efficiency (exergy) of the system are 44.6% and 12.8%, respectively; whilst the mean coefficient of performance, COP and the comprehensive coefficient of performance, COP_{pvt} of the system are 3.64 and 5.12 respectively. The heat pump system has a significant potential and benefits related to solar heat and electricity.

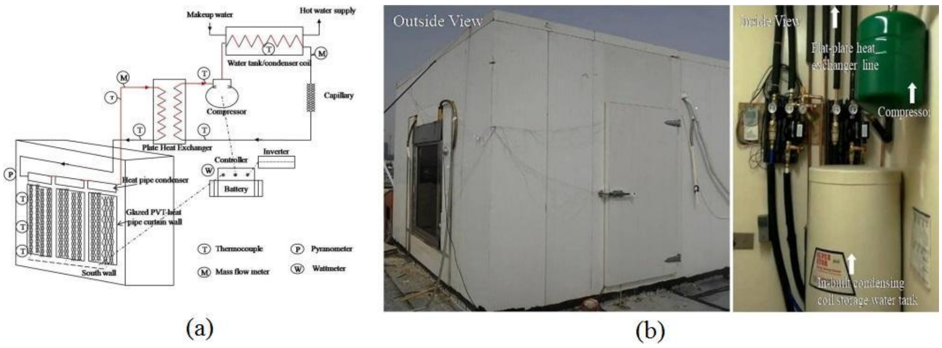

Figure 4. Schematic view of (a) IX-SAHP and (b) experimental apparatus (Tomar et. al, 2022).

2.3 ASHP

The researchers Jiang et al. (2022) compared through an experimental and theoretical study a conventional ASHP and an ASHP enhanced by solar energy for space heating in China and found that the average COP of the second system under the optimal working mode is increased by 64.4%, and the power consumption is reduced by 1.2 kWh. A theoretical study performed by Yang et al. (2022) in the United Kingdom evaluated three operating modes of an ASHP enhanced by solar energy for water and space heating after the simulation it was concluded that the yearly seasonal performance factor higher than 4.4 achievable by the three heat pumps suggests that they are potentially applied in the regions with relatively lower solar irradiance. The economic analyses indicate that the parallel and dual-source type heat pumps provide good alternatives to replace the gas-boiler heating system. In another theoretical investigation for water heating in China, Biao et al (2022) simulated a SAHP integrated with an absorption heat pump (AHP) enhanced by wind and solar energy, their results showed that the integrated heat pump can produce heating water at 50 C or even higher with a COP of about 1.42 when the environment temperature is as low as -30 C. Also, the power consumption of the ASHP accounts for only 5%–18% of the total energy input. This indicates that the energy consumed by the integrated heat pump can be mainly from off-peak electricity produced by the wind turbine. Xinzhuang et al (2022), developed a theoretical and experimental ASHP enhanced by solar energy in China for in-bin grain application concluding that the operating cost of SAHP grain drying decreased from 5.57 $/t to 1.43 $/t compared with the grain drying machine for the same drying weight. The daily drying capacity increased from 166 t/d to 334 t/d compared with the mechanical ventilation drying for the same water content reduction rate.

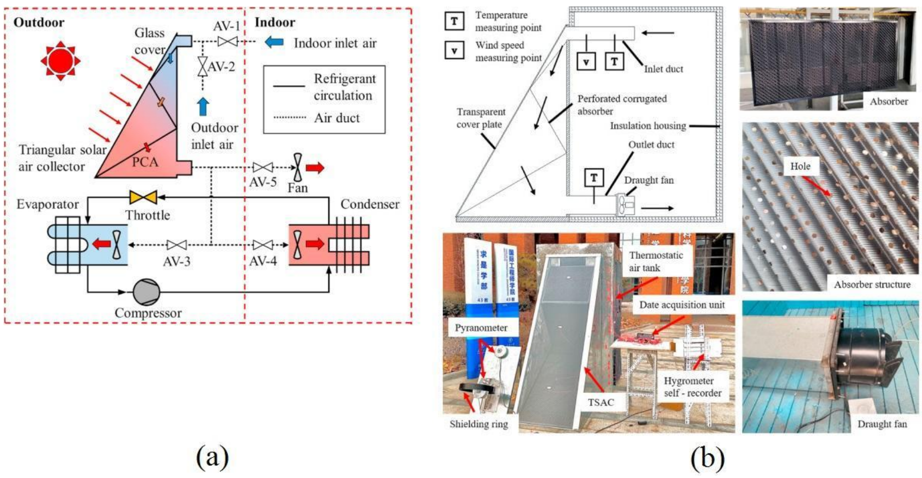

Figure 5. Schematic view of (a) ASHP and (b) experimental apparatus (Jiang et al., 2022).

2.4 SGHSHP

In an experimental study for space and water heating in Denmark, depicted on Fig. 6, the focus of the investigation was on the dynamic thermal behaviors of the heat storage under different operating conditions. When the storage was primarily heated by solar energy, the inlet stratifier in the storage performed well, ensuring thermal stratification and a good utilization of solar energy. Water temperature in the storage reached up to about 68 C at the end of the solar heating process (Zhang et al., 2022). In South Korea Lee et al. (2022) developed a theoretical analysis about SGHSHP for water and space heating application and their results showed that SGSHP with a parallel configuration decreased the energy consumption by 19.6 and 13.8% compared to those for the GSHP and SGSHP with a serial configuration, respectively, owing to an improved heating capacity. Furthermore, an SGSHP with a parallel configuration can considerably decrease initial costs by reducing the borehole length. Nahavandinezhad and Zahedi (2022), conducted a study on SGSHP for water and air heating and cooling in Iran and found that the optimal operating point was introduced with 4957/10667 kWh electricity consumption/production. Besides, an economic analysis was estimated for the optimal strategy with an investment return of 7 years. The designed system prevented 5089 kg CO_2 emissions annually. Another theoretical study based on SGHSHP for water heating in Turkey showed that a swimming pool heating system derived the majority of its total energy requirement from solar energy (being 86.18%), in addition to utilizing the heat pump (being 13.82%), during the first year of operation.

2.5 PVT-SAHP

Referring to PVT-SAHP Leonfort et al. (2022), developed in Italy an experimental model for space and water heating and cooling whose results of the 8-months field monitoring demonstrated that the proposed system allows enhancing the electrical and thermal efficiency of PVT collectors, maximizing the heat pump’s seasonal performance, and reducing the electricity exchange with the grid. A similar experimental study for water heating in Czech Republic stated that the PVT-SAHP average day indicator results showed 83% renewable energy share, 220% self-sufficiency ratio, 41% heat pump self-consumption and 46% of the solar fraction (Sanz et al., 2022).

3. PERFORMANCE MATHEMATICAL FORMULATION

The most seen formulation to evaluate the performance of a SAHP in the scientific community is the Coefficient of Performance (COP), this parameter is calculated as the ratio between the heating output (Q_{SYS}) to the total work input (W_{SYS}) applied to the system. It is calculated by (Buker and Riffat, 2016):

$$COP_{SYS} = \frac{Q_{SYS}}{W_{SYS}} \quad (1)$$

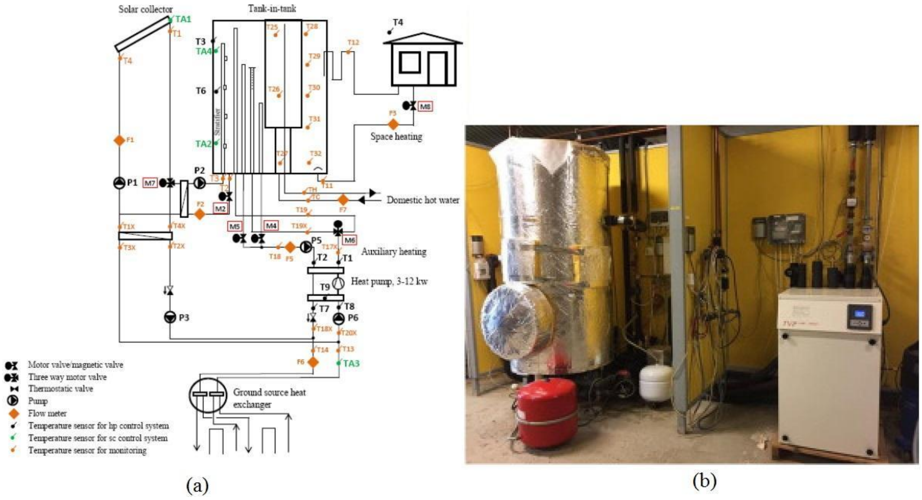

Figure 6. Schematic view of (a) SGHSHP and (b) experimental apparatus (Zhang et al., 2022).

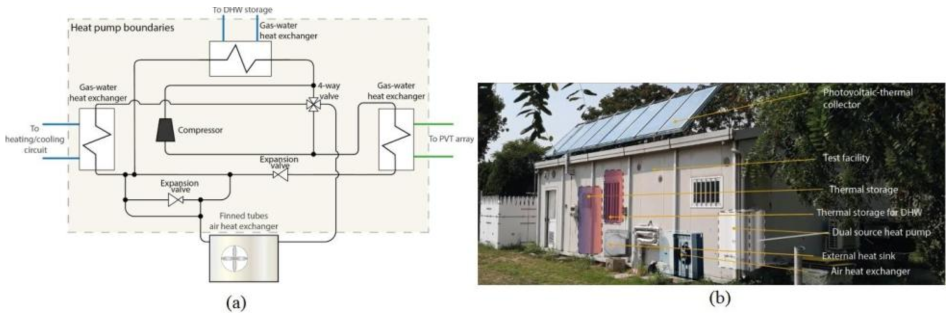

Figure 7. Schematic view of (a) PVT-SAHP and (b) experimental apparatus (Leonfort et al., 2022).

The Eq. (1) can also be expressed as follow, according to Omojaro and Breitkopf (2013), for a DX-SAHP:

$$COP_{SYS} = \frac{m_f c_f \Delta T}{W_{comp} + W_{pump} + W_{valve}} \quad (2)$$

In Eq. (2) the mass flow rate, specific heat and the temperature difference are represented by *m*, *c*, ΔT, respectively. The subscript *f* represents the fluid.

For the IX-SAHP Eq. (1) can be expressed as (Bakirci and Yuksel, 2011):

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

The mass flow rate, specific heat capacity and the temperature difference across the system are represented by *m*, *c* and T_{cwo} - T_{ewi}. The subscripts, *con*, *w*, *cwo*, *ewi*, *comp* and *p* represent condenser, water, condenser water outlet, plate heat exchanger water inlet, compressor and circulation pump, respectively.

According to the research conducted by Kong et al. (2011), in SAHP system COP increases with the increase of solar radiation intensity (I_T), this is mainly because of two reasons: (i) the increase of I_T enables to attain a higher evaporating temperature of the refrigerant, consequently resulting in a higher system COP; (2) for a given ambient air temperature (*t*a), the higher I_T enables the temperature of the collector plate t_p to increase, which results in the change of temperature difference between t_p and t_a. When t_p is lower than t_a, the collector/evaporator could obtain useful energy gain from the surroundings. The ambient temperature also contribute positively to increase the COP. That occurs because the rising *ta* lowers the heat loss from the collector and raises the fluid temperature in the collector, which results in higher COP. In relation to the compressor speed it was stated that an increase in this parameter is responsible to a decrease in COP as a result of the compressor work increment. It in turn is related to the raise in the discharge temperature associated to the increment in the compression irreversibility with speed.

The results of COP found in recent studies are summarized in table 1.

Table 1. Coefficient of Performance – COP of recent studies on SAHP.

Authors	**Year**	**Country**	**System type**	**Analysis method**	**Application**	**COP values**
Dai *et al.*	2022	China	DX-SAHP	Theoretical	Liquefied natural gas vaporization	6.52
Sivakumar *et al.*	2022	India	DX-SAHP	Theoretical and experimental	Space heating	3.1 / 3.24
Xiao *et al.*	2022	Germany	IX-SAHP cascaded system	Theoretical	Space heating	max. 8.0
Tomar *et al.*	2022	Hong Kong	IX-SAHP enhanced by PV heat pipe	Theoretical and experimental	Water heating	3.64
Jiang *et al.*	2022	China	ASHP enhanced by solar energy	Theoretical and experimental	Space heating	max. 5.5
Yang *et al.*	2022	U.K.	ASHP enhanced by solar energy	Theoretical	Space and water heating	4.4 / 4.5 / 5.5
Biao *et al.*	2022	China	ASHP + AHP enhanced by solar and wind energy	Theoretical	Water heating	1.42
Xinzhuang *et al.*	2022	China	ASHP enhanced by solar energy	Theoretical and experimental	In-bin grain drying	4.77 / 4.94 / 5.2
Zhang *et al.*	2022	Denmark	SGHSHP	Experimental	Space and water heating	max. 5.7
Lee *et al.*	2022	South Korea	SGHSHP	Theoretical	Space and water heating	max. 6.2
Nahavandinezhad and Zahedi	2022	Iran	SGHSHP	Theoretical	Space and water heating, cooling	4.39 / 3.87
Ilgaz and Yumrutaş	2022	Turkey	SGHSHP	Theoretical	Water heating	4.8 - 7.7
Leonfort *et al.*	2022	Italy	PVT-SAHP	Experimental	Space and water heating, cooling	3.0 - 3.8
Sanz *et al.*	2022	Czech Republic	PVT-SAHP	Experimental	Water heating	1.4 - 4.3

4. CONCLUSION

The SAHP is a promising technology that continuously gain market share in the heating applications and responsible for support the decrease of the ozone layer depletion and the CO_2 emissions as it replaces old equipments that use fossil fuels. Some great challenges still in the path to make this technology broad used and standardized. Researchers of many countries develop studies based on the system efficiency and the integration with other renewable energy sources to be in line with the net zero emission targets.

Further improvements on system configuration, environmentally friend refrigerants, control strategies to maximize COP during the solar irradiance variation, preventing heat losses in the thermal energy store are some of the interest themes that can be investigated.

This article made a review on SAHPs and integrated renewable energy sources configuration and performance calculation. The information presented contribute with other researches and professionals interested in the SAHP technology.

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