Analysis of the Potential of Solar-Assisted Heat Pumps: Technical, Market, and Social Acceptance Aspects

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Solar-assisted heat pumps have the potential to increase the share of renewables in the energy systems for several cases, or to increase the flexibility of smart grids and integrated thermal-electric grids. The development of such systems requires a comprehensive approach in which technical, market, and social acceptance are all tackled at the same time. Such a holistic approach is the main objective of the present review article. To do so, an investigation is performed by categorizing the integration approaches reported in the literature, exploiting the solar source either as a low-temperature evaporator source or as supporting the condenser during heating operation. Furthermore, hybrid integration schematics and dual-source approaches are discussed. Market and social aspects complete the analysis, with the aim of finally identifying the current status; the main drivers and challenges are also addressed. The reported results confirm that the exploitation of solar thermal energy can increase the achievable performance of heat pumps in a broad range of climates. A favorable regulatory/financial framework and informative campaigns for businesspersons and the wide public have been identified as the main solutions to maximize the deployment of the technology in the coming years.

1. Introduction

The energy sector is currently shaken by two major issues, climate change and its increasingly devastating effects on the environment worldwide and the COVID-19 pandemic, that highlighted the need for a secure, resilient, and affordable energy system.[1] In particular, renewable markets, especially electricity-generating technologies, have already shown their resilience to the crisis.[2] It is therefore needed to make stronger efforts to increase the penetration of renewable electricity in the heating and cooling sector by a massive deployment of heat pumps in the household building and industrial sectors. Solutions suggested at international level to reach this target include the adoption of system-oriented solutions (to optimize whole energy use)[3] and policies that can remove market barriers. An alternative that allows the efficient use of renewable (solar) energy while maintaining high efficiency levels is solar-assisted heat pumps (SAHPs).[4] Different aspects of heat pump technology have been analyzed in the recent past, including modeling,[5] the different fields of application,[6] chronological review of advancements during the last century,[4] control issues, and the different configurations at system level.[7,8] In the open literature, focus has been put mainly on air source[9] and ground source heat pumps,[10,11] whereas other cases are less exploited.

Considering the SAHPs from a systematic point of view, renewable-driven operation is only possible if the heat pump itself is integrated with other devices, such as thermal storages and solar collectors. Different thermal storage technologies have been investigated for enhancing the performance of the heat pump,[12–14] mainly focusing on the effect of the storage on the heat pump size and the effect of storage on the overall amount of renewable energy that can be exploited by the solar-assisted system.[15,16] Solar collectors and their installation in conjunction with heat pumps are discussed, for instance, in the study by Kamel et al.[17] Photovoltaic (PV) systems are the most common solution for solar-driven heat pumps, whereas the photovoltaic/thermal (PV/T) systems, despite being widely studied, are less common due to the increased complication at system level. In Poppi et al.,[18] the technoeconomic analysis of solar heat pump systems is discussed, by comparing the merit of the different configurations especially in economic terms.

The SAHP topic has been already presented in the literature by other review articles. Among the most recent ones, Yang et al.[19] presented an accurate investigation about the most recent advances in solar-assisted air source heat pumps, focusing on domestic applications. In particular, they presented different integration schematics and possible improvements to be applied to make the technology more attractive. Fan et al.[20] focused the investigation of the most recent progresses in SAHP, trying to identify the most critical technology challenges and presenting a new technology to efficiently couple solar technologies with heat pumps. Sezen et al.[21] approached the review of SAHP applications focusing on the effect of ambient conditions over the overall achievable performance, in order to identify the most relevant parameters to consider and optimize the applicability of SAHPs under different climates. Lazzarin[22] investigated in a

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The ORCID identification number(s) for the author(s) of this article can be found under https://doi.org/10.1002/solr.202200037.

DOI: 10.1002/solr.202200037

broader way the possibility of coupling solar thermal technologies with different heat pumps, also looking at the historical evolution of the development activities. Nouri et al.[23] discussed the technical feasibility of solar-assisted ground source heat pump, trying to highlight the benefits and most relevant applications. Shi et al.[24] focused their literature review on the solar-assisted direct expansion heat pumps technology, considering multiple aspects such as the system configurations, performance optimization, and modeling activities. Mohanraj et al.[5,6] presented a broad investigation about numerical and experimental implementation of SHAPs, investigating the potentiality, from the technical point of view, in different application fields, e.g., drying, space heating, green house space heating, water heating, and desalination. Wang et al.[25] dedicated their literature analysis to the application of SAHP in the field of domestic hot water (DHW) generation, considering technical, economic, environmental, and social acceptance perspectives.

Starting from the analysis of the published reviews, the main novelty of the present work is based on a novel approach for the SAHP analysis, taking into consideration technical, environmental, commercial, and social aspects, structured as follows: 1) In Section 2, the main technical aspects related to SAHP application for space heating, cooling, and DHW provision are discussed, proposing a source/sink-based classification of the technologies and investigating the most recent advancements reported in the literature. 2) Section 3 focuses on different applications in which SAHPs can be applied, considering both already implemented sectors such as drying and innovative complex systems exploiting solar resource and heat pumps for heating and cooling purposes. 3) Section 4 provides a critical analysis related to the optimal conditions for the integration of solar resource and heat pumps as well as the analysis of the most relevant climatic conditions affecting the SAHP technology. 4) Section 5 analyzes the current market situation for heat pumps especially connected to solar technologies. 5) Section 6 investigates the social acceptance aspects related to these innovative solutions. 6) Section 7 provides the main conclusions of the literature investigation as well as future perspectives for the further development and implementation of the SAHP technologies.

2. Solar-Coupled Vapor-Compression Heat Pumps for Space Heating/Cooling: Technical Aspects

2.1. Systematic Classification of Heat Pumps according to the Source/Sink Approach

A systematic method for the classification of heat pumps using the source/sink approach was developed, starting from thermal hybrid systems, within IEA Task 44 and is described in the study by Fedrizzi et al.[26] The source–sink table established fully describes the system from the point of view of the existing fluxes among components and, in addition, provides a suitable nomenclature for the identification of the heat and electricity fluxes based on their source and sink. The following parameters are used for the classification of SAHP, according to the framework presented in the study by Frank and Haller[27] whose flexibility was validated through a simulation tool based on TRNSYS, for simplified simulations of the different configurations:[28] 1) the sources of the heat pump; 2) the sinks of the heat pump; 3) the typology of solar collector (i.e., solar thermal, solar photovoltaic, PV/T); 4) the sources of the solar collector; 5) the sinks of the solar collector; 6) the presence of storages; and 7) the operation (i.e., the useful effect delivered).

The nomenclature used for the scope is presented in **Table 1**.

The different cases examined and the application of the source/sink approach in the present analysis are shown in **Figure 1**. The different source and sink conditions are strongly linked to the different applications. The idea is to define a common framework to classify and analyze the different options. Of course, the specific application and the system in which each technology can be applied are clarified case by case.

2.2. Solar Source—Space Heating/Cooling Distribution Sink and Direct Expansion Configuration

One of the possible layouts for SAHPs, which is among the most used for its simple integration, is the serial connection between the collectors and the heat pump, where the refrigerant directly flows through the solar collectors, undergoing evaporation process, as shown in **Figure 2**.

In this configuration, the heat pump extracts the thermal energy required from the solar evaporator/collector that can be a solar thermal system or a PV/T one. The cooling effect of the refrigerant reduces the working temperature of the PV part of the PV/T modules; therefore, this integrated PV/T-SAHP exhibits a relatively high thermal performance with improved coefficient of performance (COP) and PV efficiency compared to other configurations.[29,30] In general, the operation of this type of HP is strongly linked to ambient conditions: by increasing solar radiation and temperature, COP increases due to an increased evaporation temperature[31] and PV electric efficiency increases due to the cooling effect of the collector.[32]

Another advantage of this layout for PV/T-assisted HPs is the possibility of actually designing a PV/T roof with insulation properties and rain protection, also generating electricity and useful heating effect. The integration aspect in building has not been fully exploited yet because most of relevant literature mainly deals with building-integrated PV. Design specifications and energy considerations on the effect of PV/T on building loads are given in the study by Shao et al.[33] Average thermal and overall efficiency of PV/T roof estimated are 69.3% and 86.8%, respectively. Compared to PV roof (system under PV mode), both electricity production and electrical efficiency of PV/T roof (system under PV/T mode) increased by 12% and 10.8%,

Table 1. Nomenclature for the classification of heat pumps according to the source/sink approach.

Air	Air	srS	Source storage
Sol	Solar radiation	skS	Sink storage
S	Solar collector	SH	Space heating
HP	Heat pump	SC	Space cooling
W	Water	DHW	Domestic hot water
DHWDS	DHW distribution system	HDS	Distribution system for heating
		CDS	Distribution system for cooling

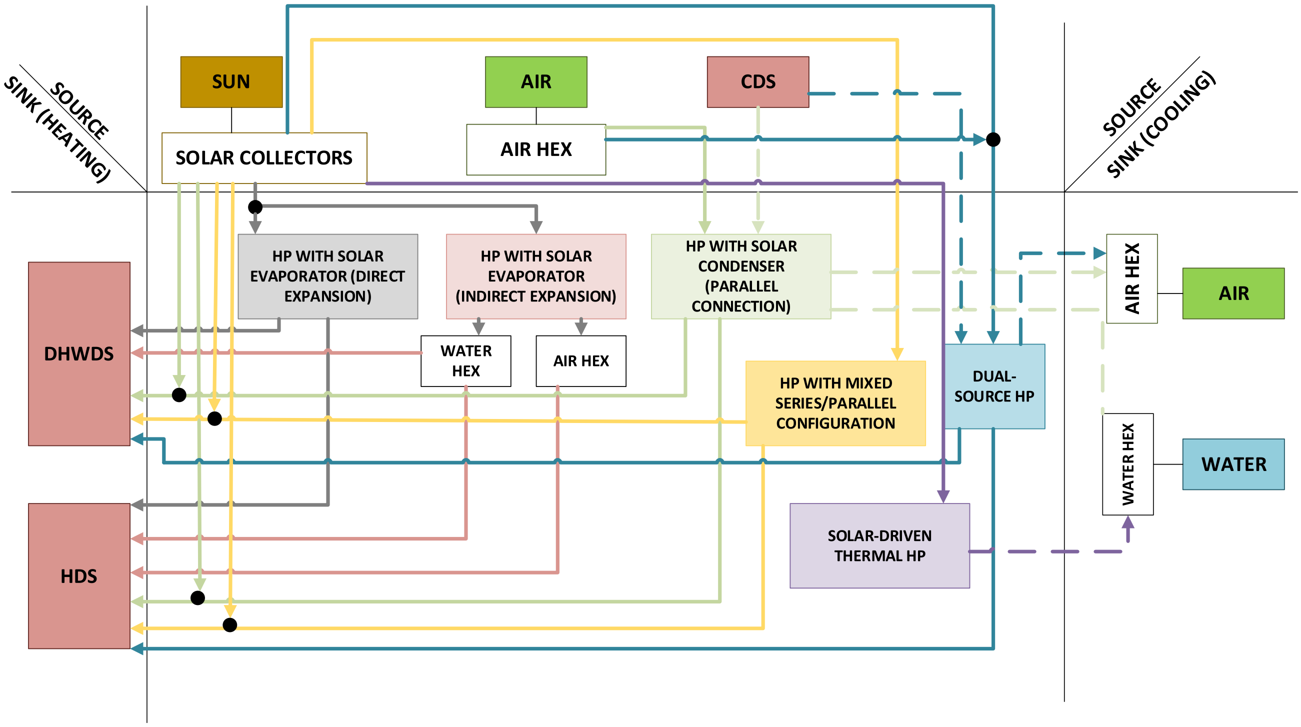


Figure 1. Source/sink approach for SAHPs. Dashed lines are used to indicate the sink of HPs in cooling mode.

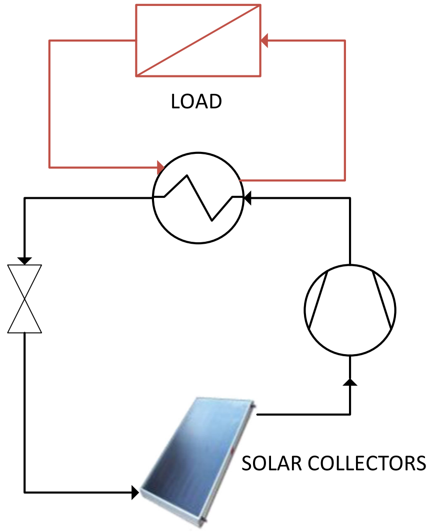


Figure 2. Solar evaporator and direct expansion configuration.

respectively. Moreover, the PV/T roof can effectively lower the energy consumption of buildings, reducing the heating gains and daily load by 39.9% and 38.6%, respectively.

Given the advantages due to the direct expansion configuration, several researches are currently focusing their research activities on the optimization of components and cycles for this type of direct expansion SAHPs. For instance, in Zhou et al.[34] a heat pump using a microchannel evaporator is studied both numerically and experimentally under climatic conditions of Lvliang, China. The results indicated a strong dependence of thermal and electric efficiency and COP from solar radiation because higher daily temperature leads to higher evaporation temperatures and consequently higher temperatures on the PV/T modules. The overall surface of the PV/T-evaporator modules ($22\,m^2$) was enough to provide about $1300\,kWh\,month^{-1}$ during winter conditions, which was the expected target for the system. The introduction of microchannel technology allows enhancing the heat transfer process in the fluid interface; the refrigerant evaporation rate and the consequent electrical and thermal performance increase were the most evident outcomes. Another application of a microchannel collector/evaporator and a microchannel condenser are reported in the study by Kong et al.[35] The main aim for choosing such a configuration is the need to reduce the refrigerant charge, since R290 is used, which is a low-GWP flammable refrigerant. The HP is studied experimentally under heating mode in winter conditions. The results demonstrate that COP ranged from 2.12 to 4.43 under the average solar radiation intensity of 20–592 $W\,m^{-2}$, average ambient temperature of −3.0 to 12.2 °C, and average wind speed of 0.01–1.15 $m\,s^{-1}$, when the 200 L water at 7.2–15.3 °C was heated to 37.7–54.9 °C. Results also indicated the need to optimize the design of the microchannel heat exchangers to reduce pressure drops and to promote refrigerant flow while guaranteeing a stable operation of the expansion valve, which is a critical component in such a configuration. To solve such issues, i.e., the regulation stability of the expansion valve to keep the superheating in the desired range, and to mitigate the effect of variable solar radiation during daytime, different studies proposed a variable speed strategy[36,37] using R134A heat pumps which basically consists in increasing the speed of the compressor with the increasing evaporation temperature. This approach allows reaching a more constant evaporating temperature even under ambient temperature variations and the deceleration mode of the compressor speed enables to stabilize the compressor power. Finally, a quasidynamic model of the DX-SAHP water heater was performed and showed that, through proper control of the speed of the compressor, it is possible to improve energy efficiency and stability of the DX-SAHP systems. On the contrary, for a small-size CO_2 DX-SAHP, the results presented in the study by Rabelo et al.,[38] which are also compared to previous literature works, show that, for this specific refrigerant, the effect of the opening of the expansion device on electricity consumption of the compressor (and therefore COP of the HP) is negligible. Accordingly, the authors suggest using a static expansion device as a capillary tube, thus reducing the costs of this equipment. However, the results on a direct expansion SAHP using CO_2 discussed in the study by Paulino et al.[39] showed that a small variation of the solar radiation leads to a significant variation in the superheat, therefore requiring an immediate action of the expansion device. Therefore, the use of an electronic expansion valve (EEV) was suggested, which allows a steady and continuous flow of refrigerant.

Several attempts were also made to improve the design of solar collectors to boost solar yield under typical operation with heat pumps. The main difficulty, compared to standard PV/T design, is due to the combined effect of flow channel patterns, solar radiation, ambient conditions, and possible condensation and frost formation.[40] To model it, a resistance–capacitance model based on electric-thermal equivalence is presented in the study by Rullof et al.[40] and applied to a transcritical CO_2 SAHP. Another approach is followed in Ran et al.[41] In this study, the heat pump uses a multifunction evaporator that can work with both air and solar energy sources according to solar availability. All the operations are realized through a single evaporator/collector. The primary energy efficiency of the proposed system is in the range of 0.97–1.14, with energy saving rates of 48% and 66% compared with air source heat pump and the conventional solar heating system, respectively.

A specific issue faced in such integration is represented by the formation of frost on the solar collector/evaporator module. Its effect is studied, for instance, in refs. [42,43] using a prototype and an experimentally validated dynamic model. Results indicate that even under frosting conditions, the system shows reliable heating performance and that there is a delay in frosting compared with the traditional evaporator of air source heat pump. Moreover, decreasing the ambient temperature below a specific value can effectively inhibit the formation of frost. At low humidity and higher wind speeds, similarly, the frosting rate is reduced or no frost formation is observed. The collector efficiency can also be improved effectively during the incipient growth of frost crystals. The special value is about 1 °C when the solar radiation intensity, the relative humidity, and the wind speed are 100–350 $\mathrm{W\,m^{-2}}$, 70–90%, and 1–5 $\mathrm{m\,s^{-1}}$, respectively.

As for all HPs applications, the search for new refrigerants and the tendency to use natural refrigerants in recent years are leading to verification, through numerical and experimental activities, of the feasibility of new refrigerants and their mixtures under the specific operating conditions. In Paradeshi et al.,[44] the energy performance of a direct expansion SAHP system, working with a hydrocarbon mixture of R290/R1270, 70:30, is compared with the same system using R22 under realistic conditions of Calcutta. It is found that the selected alternative working fluid mixture has COP about 5.8% higher.

Technoeconomic analysis was also performed to optimize the components' design and selection and to define the feasibility of these HPs at system level. In De León-Ruiz et al.,[45] genetic algorithms and artificial neural networks are used for a multiobjective optimization. Parameters used for the optimization include the number of solar collectors and different working fluids. Among them, R410A is the most performant one, followed by the R407C, R404A, and R134a. However, the R134a refrigerant requires the lowest compression work input. It is interesting to notice that, despite changes on weather or design conditions, all refrigerants perform within or beyond the minimum expected performance range, with COP levels higher than 3. In Qiu et al.,[46] a model of a novel integrated system of solar collectors and air source heat pump is proposed, in which two stages of compression are foreseen. The idea behind the system is to have the solar collectors working at a medium temperature level between the evaporator and the condenser, which represents an intermediate case between the application on the condenser side only (which is mainly suitable for high solar radiation intensity and high outdoor temperature) or the evaporator side only (mainly fit for low solar radiation intensity and low outdoor temperature). The schematics for the system are shown in **Figure 3**. In this way, the operating range of the SAHP can be extended.

The studies related to direct expansion SAHPs are summarized in **Table 2**, following the source/sinks approach as presented in Figure 1.

2.3. Solar Source—Space Heating/Cooling Distribution Sink and Indirect Expansion Configuration

Another layout for the serial connection between the collectors and the heat pump is the indirect expansion configuration, in which the refrigerant does not directly passes through the solar collectors, but instead absorbs heat for evaporation from the heat transfer fluid of the solar loop, as shown in **Figure 4**. It is possible to have two different integrations, with an external heat exchanger and without a storage tank (Figure 4a) or by connecting the solar collectors through a storage tank acting as a buffer (Figure 4b). In this case, the heat exchanger is directly immersed in the tank.

The main advantages of this configuration, as highlighted, for instance, in the study by Vallati et al.,[47] are the possibility of supplying heating using evaporation temperatures that range

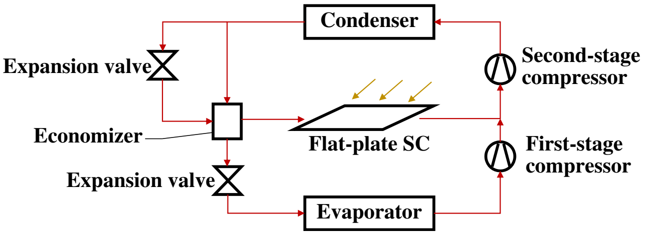


Figure 3. Medium-temperature solar collector configuration as discussed. Reproduced with permission.[46] Copyright 2022, Elsevier.

Table 2. Studies on direct expansion SAHPs. Nomenclature: E, experimental; N, numerical; EN, experimental and numerical; CO, electric power compressor; H, heating power.

Solar type	Study	Operation	Solar collector sources	Solar collector sinks	HP sources	HP sinks	Refrigerant	COP	Power [kW]	References
ST	N	SH	Sol	HP	S	HDS	R32	2.8–4.5	5.5–8 H	[29]
PVT	EN	SH	Sol	HP	S	HDS	a	4.84–7.03		[30]
ST	E	SH	Sol	HP	S	skS	R134A	3.6–4.6	0.56 CO	[31]
PVT	E	SH	Sol	HP	S	HDS	R134A	2–5.5	0.198 CO	[32]
PVT	E	SH	Sol	HP	S	skS	–		7.8 CO	[33]
PVT	E	SH	Sol	HP	S	skS	R410A	4.7	3.75 CO	[34]
ST	E	SH	Sol	HP	S	skS	R290	2.12–4.43	0.26–0.34 CO	[35]
ST	E	SH	Sol	HP	S	skS	R134A	2.55–6.71	0.15–0.45 CO	[36]
ST	N	SH	Sol	HP	S	HDS	R134A	2.75–4.24	0.26–0.43 CO	[37]
ST	E	SH, DHW	Sol	HP	S	HDS, DHWDS	R744	1.7–2.9	0.6–0.64 CO	[38]
ST	EN	SH	Sol	HP	S	HDS	R744			[39]
ST	EN	SH	Sol	HP	S	skS	R433A	1.9–2.8	1.05–1.2 CO	[44,147]
PVT	N	SH, DHW	Sol	HP	S	skS	R744	–	–	[40]
ST	N	SH	Sol	HP	S	HDS	R410A	3.12–3.89	0.19–0.21 CO	[41]
PVT	EN	SH	Sol	HP	S	skS	R134A	4.03–6.06	0.3	[42]
ST	EN	SH	Sol	HP	S	SH	R134A	1.89–2.21	1–1.6 H	[43]
PVT	E	DHW	Sol	HP	S	skS	R404A	2.7–4.5	1.2–2.4 CO	[44]
ST	N	SH	Sol	HP	S	skS	R134a, R404A, R407C and R410A	4.8–16	4–8 H	[45]
PVT	EN	SH, SC	Sol	Hp	S	skS	R22, R290/R1270, 70:30 [wt%]	2–4.5	4 H	[148]
ST	N	SH, DHW	Sol	HP	S	HDS, DHWDS	a	1.6–5.5	8–18 H	[46]
ST	EN	SH	Sol	srS	S	skS	R134A	1.7–2.5	0.8 CO	[149]

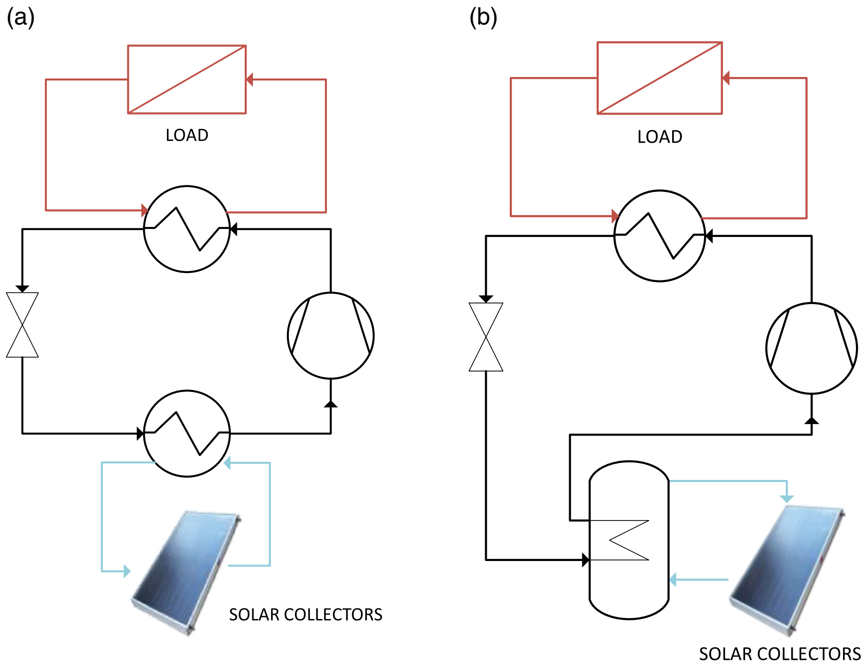


Figure 4. Solar evaporator and indirect expansion configuration a) without or b) with storage tank.

from 10 to 20 °C even in central Europe. It is, however, worth remarking that, for this specific application, the use of a thermal storage tank is foreseen in almost all the cases examined in the literature and that, for the coldest climates, the integration with a gas or electric heater cannot be avoided. In Chen et al.,[48] the operation of a heat pump coupled to PV/T panels for heating and DHW purposes is compared to a stand-alone heat pump driven by PV panels electricity. The direct coupling of collectors and heat pump is beneficial for both components: the electrical efficiency of PV/T panel is about 25% higher and the COP of the heat pump increases by 22%. Similarly, the benefits of this kind of connection are discussed in the study by Cao et al.[49] where a TRNSYS model for a SAHP operating in a low-temperature region is developed. Results indicate that, if a proper control strategy is applied and a storage tank is used, the HP can operate with COP in the range of 3.6–4.9, thus indicating the good potential of this solution for the applications in low-temperature ambient conditions.

Several research studies are devoted to the development of optimized components. For instance, in Zhou et al.[50] a HP with a minichannel evaporator directly embedded in the solar collector is investigated that has a higher heat transfer capability than a standard plate evaporator. Moreover, the integration of the evaporator in the solar collector allows an increase in the overall solar fraction that the system can achieve.[51]

The optimization of the solar collectors coupled to this type of heat pumps is also being pursued and different solutions have been studied. In Lee et al.,[52] a flexible solar collector is used, for its lower cost and easier installation. A schematic of the main components of the flexible solar collectors is shown in **Figure 5**. Apart from the inner tube, made of aluminum, the other components are realized in polyethylene film. The SAHP is tested using two different refrigerants: R134a and R-1233zd(E). The results indicate that the flexible solar collector has an average efficiency of 40% under a variable range of solar irradiation and ambient temperatures range, thus making it a viable solution for cold and Northern climates. Further increase in the HP performance is achieved by controlling the mass flow rate and heat source temperature of the working fluid.

Another innovative solar collector evaluated in combination with SAHP is a nanofluid-based hybrid PV/T collector described in the study by Bellos et al.[53] Different nanofluids are used as working fluids in the solar collector with the aim of enhancing both the thermal and electrical performance by increasing the useful power output of the collectors. In particular, water/Cu and water/Al_2O_3 are identified as the most efficient nanofluids that allow up to 5% increase in energy efficiency at system level.

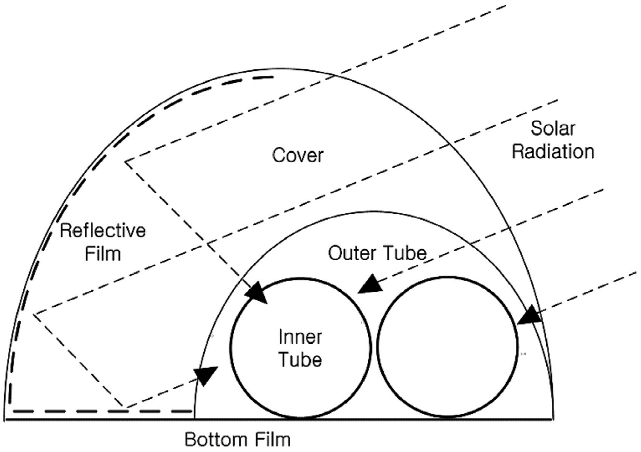


Figure 5. Flexible solar collector for SAHPs. Reproduced with permission.[52] Copyright 2018, Elsevier.

Innovation on the storage tank, by using a hybrid water-PCM design, is proposed in the study by Qu et al.,[54] where the heat pump is connected to the hybrid storage that is charged by solar collectors. Results highlight that the peak COP reached using the novel storage tank is 10, about 3.5 times higher than connecting the heat pump to a water storage tank. In Del Amo et al.,[55] the coupling of PV/T with a seasonal storage is evaluated (1500 m^3 with a 1.5 m^3 household storage). The benefit highlighted is that the seasonal COP increases because the average evaporator temperature over winter is higher than by using a short-term storage.

For this type of heat pumps, efforts have been devoted to technoeconomic optimization at system level, to identify the proper sizing, management, and operation constraints to achieve high solar-assisted operating hours throughout the year. Technical constraints generally considered for the operation include the size of solar collectors, the working fluid, and the size of the heat pump compared to the load.[56] In previous studies,[57,58] the influence of intermittent operation is assessed by analyzing the variation of key parameters which control the performance of a hybrid system, such as solar irradiance, water flow rate in the PV/T, and storage tank size. In Chen et al,[59] a sensitivity analysis is carried out to evaluate which factors affect the most the operation of a SAHP. The specific technical case considered is the use of a PV/T collector with embedded heat pipes. The parameters investigated are solar radiation, ambient temperature, supply water temperature in condenser, PV packing factor, heat pipe pitch, and PV backboard absorptivity. The parameters that have a beneficial effect (i.e., increase) on the COP of the heat pump are the increase of solar radiation, ambient temperature, and PV backboard absorptivity, while the increase of supply water temperature in condenser, PV packing factor, and heat pipe pitch lead to the decrease of COP. The effect of combining solar heat with another renewable source, i.e., a biomass heater as evaporation heat source, is described in the study by Dong et al.,[60] where different operating modes are compared. Passing from an air source heat pump to a SAHP with indirect expansion and a storage tank heated only by solar collectors, there is an increase of COP from 1.70 to 2.32, with a renewable share of 57%. When the storage tank is heated by either solar or biomass energy, the COP is 2.26, with a share of renewable energy used of 56%. Another application described in the study by Nasruddin et al.[61] is the application of a multiobjective genetic algorithm for the optimization of design parameters of a SAHP using low-GWP refrigerant for high temperatures (105 °C). COP and cost were used as objective functions, with the aim of selecting optimal suction and condensation temperatures. For suction compressor temperature of 99 °C and condensing temperature of 106 °C, a COP of 5.04 and total cost of 82 678 USD were identified. From such an analysis, it is possible to conclude that, in the indirect expansion configuration, the introduction of a thermal storage lets to achieve higher COP and energy savings in most of the analyzed works.

The studies reported in this section are summarized in **Table 3**.

Table 3. Studies on indirect expansion SAHPs.

Solar type	Study	Operation	Solar collector sources	Solar collector sinks	HP sources	HP sinks	Refrigerant	COP	Heating/cooling capacity [kW]	References
PVT	N	SH	Sol	srS	S	SH	–	4.82–5.25	9 CO	[47]
PVT	E	SH, DHW	Sol	srS, HP	S	skS	R134a	1.96–3.4	0.1–0.4 H	[48]
PVT	E	DHW	Sol	HP	S	skS	–	3.5–4.6	17.5 H	[49]
ST, PVT	EN	SH	Sol	srS	S	skS	R22	4.9	2 CO	[50]
PVT	EN	SH, DHW	Sol	srS	S	skS	R410A	4.39–5.26	29 H	[51]
ST	E	SH	Sol	HP	S	skS	R134a, R–1233zd(E) is	1.5–3.8	0.7–1.2 CO, 3.0–4.2 H	[52]
PVT	N	SH	Sol	HP	S	HDS	R152a	2.75–3.72	6.38–7.13 C	[53]
PVT	EN	SH	Sol	srS	S	HDS	–	2.32–10.03	–	[54]
PVT	EN	SH	Sol	srS	srS	HDS	–	–	–	[55]
PVT	N	SH	Sol	HP	S	HDS	R32, R1234yf, R245fa, R404A, R290, R600a	2.75–3.72	6.38–7.13 C	[56]
PVT	E	SH	Sol	HP	S	HDS	R407c	4.2–6.5	7–8 H	[57]
PVT	N	SH	Sol	srS	skS	HDS	R407c	4.2–6.2	0.053 CO	[58]
PVT	EN	SH	Sol	HP	S	HDS	R134a	2.1–4.5	0.1–0.5 CO	[59]
ST	E	SH	Sol	skS	skS	HDS	–	1.7–2.32	1.875 CO	[60]
ST	N	Steam	Sol	HP	S	HDS	R1234ze(E)	4.88–5.09	27–31 H	[61]

2.4. Air Source—Solar/Space Heating and Cooling Distribution Sink in Parallel Configuration

The operation of SAHPs can also include the installation of solar collectors to enhance the useful effect of the heat pump, and therefore connected to the condenser heat transfer fluid (HTF) loop of the heat pump. Indeed, for this connection, several alternatives exist, depending on the heat source used for providing the evaporation heat to the heat pump and the integration of solar collectors in the refrigeration cycle. The case of an air source heat pump is shown in **Figure 6**. In this case, the evaporation heat is provided by ambient air and the heating circuit is connected, by means of deviating valves, either to the solar collectors or to the heat pump (Figure 6a). The installation of a storage tank can be foreseen, with the twofold aim of compensating for the temperature fluctuations in the solar circuit and to separate the solar circuit from the condenser circuit of the heat pump. The storage tank can be charged either by the solar collectors or by the condenser (Figure 6b). In the latter case, it is also possible to exploit the tank for both DHW and space heating. However, compared to the case of serial connection of the solar collectors to the refrigeration cycle, there is the need for the external unit to provide evaporation heat to the refrigeration cycle, thus increasing the number of components and of auxiliaries, with the associated

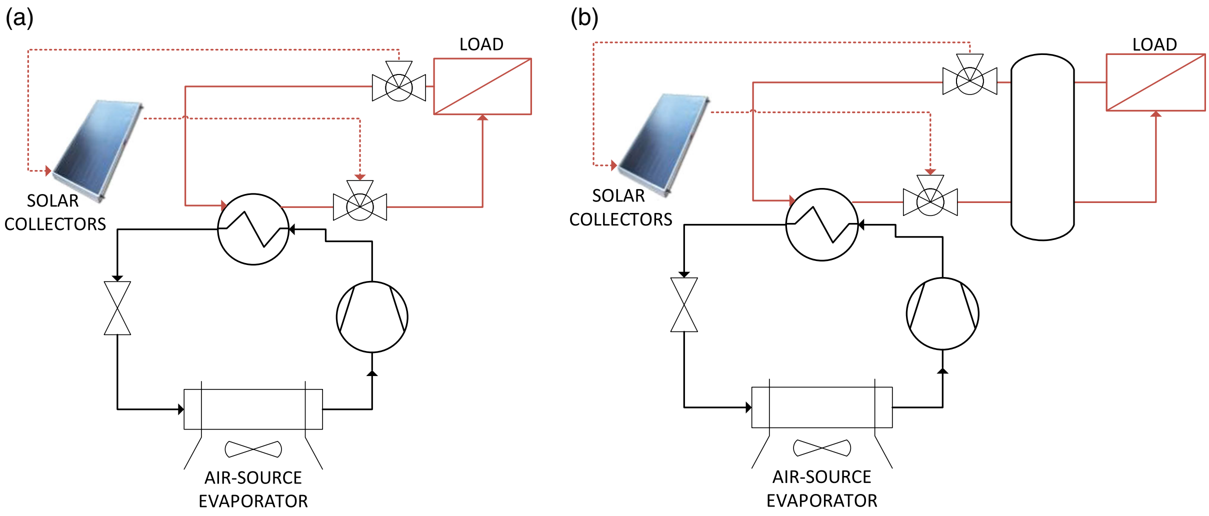


Figure 6. Solar condenser and air source evaporator configuration a) without or b) with storage tank.

parasitic consumption. It is worth mentioning that, for this configuration, the solar collectors can also work independently from the heat pump if the storage tank is foreseen in the installation.

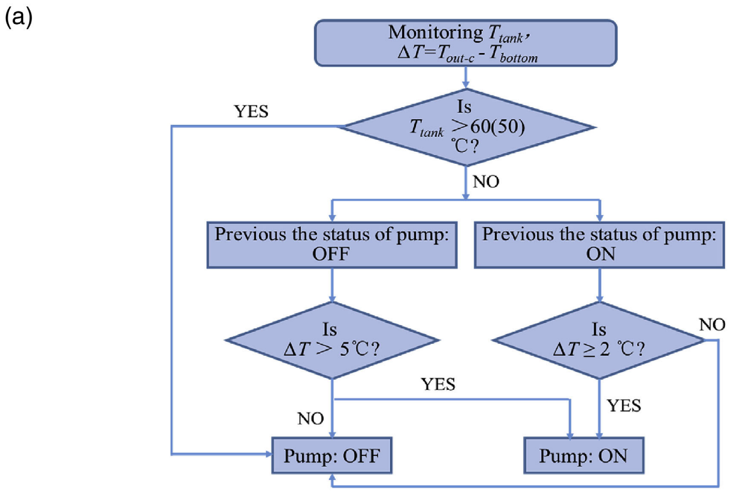
The advantages and some practical considerations for the installation of this type of system are given in the study by Jordan et al.[62] In this case, a prototype of heat pump was assembled and tested. At first, direct connection of the condenser of the heat pump with the solar collectors was used, but overpressure issues on the condenser were encountered and therefore it was decided to use an intermediate tank. The tests carried out were used to compare the energy consumption of the solar heating system operating with the heat pump and with an electrical resistance of 3000 W. Result shows that the energy consumption of the solar system with heat pump was 54.9% lower compared to the use of the resistance.

One of the main challenges in the effective application of this configuration is the design and management of the system to ensure reliable heating supply,[63] which is more complex than in the previous configurations. Accordingly, the majority of research studies are focused on these issues.

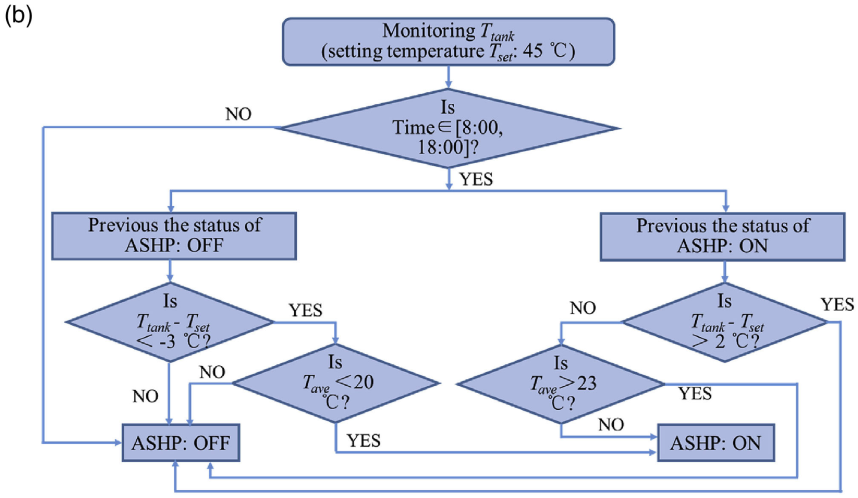
The control logic for a SAHP using an air source evaporator and designed for the application in residential/tertiary buildings of Alpine regions is shown in **Figure 7** and described in the study by Liu et al.[64] The control logic is based on the monitoring of tank and collectors' temperatures and on the indoor room temperature. Three separate controls are used for the pump in the solar circuit, for the on/off of the HP, and for the floor heating system. The control logic is integrated in a TRNSYS validated model and the results used for an energy, economic, and environmental analysis comparing the SAHP with the air source one. It is found that the control logic used can actually reduce storage tank fluctuation and, at the same time, guarantee a more stable temperature inside the building. Moreover, the SAHP has 45% less energy consumption compared to the ASHP system, with a COP 109.43% higher and a cost 10% lower on annual basis. In addition, the SAHP system produces 55.48% less carbon emissions than the air source HP. Another example of management strategy to improve the performance of a SAHP in parallel configuration is given in Shan et al.[65] where a configuration with no water tank on the collectors' circuit is investigated. In this case, two threshold limits are used to control the on/off of the SAHP and of the solar collectors' circuit, 25 °C (minimum threshold for starting the solar-assisted operation of the heat pump) and 38 °C (maximum temperature to be reached in the storage to stop the heat pump). The user circuit was further controlled by a thermostat that kept the temperature in the room at 16 °C. The results indicate that to maximize energy savings, the heat pump should be started only during periods with high ambient temperatures (e.g., afternoon) instead of periods of low ambient temperatures (e.g., midnight). In this way, it is possible to improve the COP by 20% compared to air source operation. Moreover, the critical parameters for improvement of system performance were identified: the utilization of the thermal inertia effects of heat storage from radiant floors, use of hot water tank connected to the solar collectors, and use of weather forecast technologies for definition of on/off periods of the heat pump. In Chen et al.,[66] the operation of a CO_2 heat pump is investigated using experimental data and a validated TRNSYS model. As in the previous cases, two separate controls are used for the heat pump/solar collectors and the user side based on the temperatures in the solar circuit and the ambient. The technical parameters evaluated are the volume of the storage tanks on the solar and user sides. On the solar side, increasing the size of storage tank volume increases the total storage capacity and reduces the temperature of the solar collectors' array, which leads to a high efficiency. However, there is a value beyond which it is detrimental to increase the storage volume because the limited extension of solar collectors does not allow for enough power to heat up the whole volume and this increases the operating hours and power from the HP, thus penalizing the operation of the heat pump. On the user side, a bigger tank allows a lower fluctuation in the temperature of the tank, thus reducing the load and the electricity consumption of the HP. However, when the operation tank volume reaches a critical value, the heat losses of the whole tank become an important factor, especially when the CO_2 HP operates alone. In this case, the growth of total heat demand leads to the increase of electricity consumption of the CO_2 HP. These parameters were then simultaneously varied using a multiobjective optimization algorithm in GENOPT. The optimized system can save 14.2% electricity and improve the solar fraction by 8% compared to first design. The optimal strategy to operate a parallel air–water SAHP in regions with shortage of solar energy and during transition seasons is discussed in the study by Liu et al.,[67] to provide DHW with the maximum solar fraction possible. The suggested strategy, based on the optimization of a validated model and experimental data, is to switch on the HP 1 h before using when the average ambient temperature is below 20 °C, and to switch it on at the hour with the highest temperature of the day when the average ambient temperature is above 20 °C and operate it for 1 h.

One of the main issues in the design of the system is the presence of several uncertainties, mainly due to uncontrolled weather data and system control parameters. In order to take into account the effect of such uncertainties, in Li et al.[68] a methodology is proposed, based on Monte Carlo simulation to propagate the input uncertainties of the solar fraction and system efficiency. Based on simulation outcomes, the input parameters are ordered by significance and the optimal solar fraction for different districts in China is given, which guarantees the economic dependability of the system.

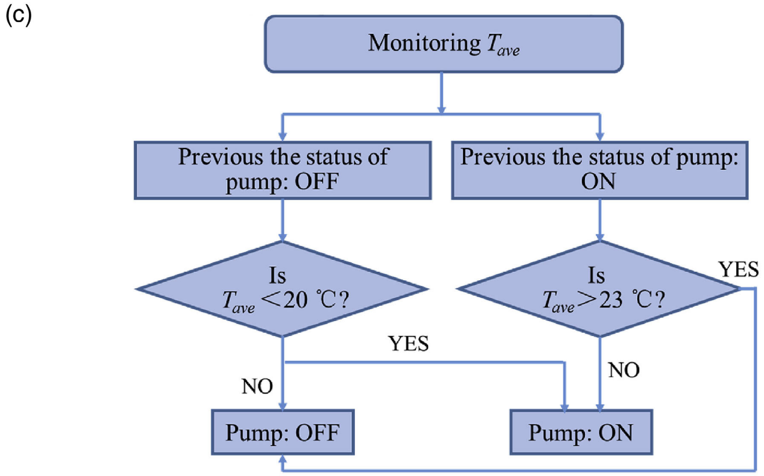
Economic profitability of a SAHP system compared to air source heat pump is presented in the study by Poppi et al.,[69] where an extensive sensitivity analysis is done to define the influence of several technical parameters on the economic profitability of the system. In the cold climate investigated (i.e., Switzerland), the parameters that bring an improvement in system performance are the variable speed compression (over a fixed point one) and the vapor injection cycle, whereas the effect of storage vacuum insulation and four-pipe connection is not justifiable. The predominant effect of supply water temperature for heat pump performance is also the outcome of the system design analysis presented in the study by Zhao et al.[70] The proposed system is intended for application in regions with low solar radiation and includes a solar phase change thermal storage (SPCTS) heating system using a radiant-capillary-terminal (RCT) to effectively match the low-temperature hot water, a phase change thermal storage to store and continuously utilize the solar energy, and an air source heat pump. Two operating modes are allowed:



Logical control of solar collector system.



Logical control of ASHP system.



Logical control of indoor heat supply system.

Figure 7. Control logic of a SAHP for Alpine regions. Nomenclature for the figure: T_{ave}, average room temperature; $T_{out,c}$, outlet temperature of solar collectors; ASHP, air source heat pump. a) Logical control of solar collector system; b) logical control of ASHP system; c) logical control of indoor heat supply system. Reproduced with permission.[64] Copyright 2022, Elsevier.

the first is the direct supply of RCT by SPCTS if the solar radiation is enough, and the second is the activation of heat pump when the solar energy is low. Indeed, the results of the analysis indicate that to profit from solar-assisted operation and keep comfort conditions indoor, the better condition is to use a floor heating system and a supply water temperature of 35 °C. In order to further improve the performance of the integrated system, the ASHP heating system should be operated during daytime because the efficiency of ASHP is inversely proportional to the ambient temperature, and the SPCTS, after storing thermal energy in the PCTS tank during daytime, should be operated during night.

Economic aspects connected to the installation and operation of SAHPs are also discussed in the study by Pinamonti and Baggio,[71] where different configurations are compared to a reference system, i.e., an air source stand-alone HP considering heating and cooling demand of buildings with different construction features. In particular, PV and ST are compared in terms of energy and economic savings. Results indicate that solar thermal is the preferable solution for a low insulated building, whereas for medium and highly insulated building, PV installation with electric storage is the most profitable solution considering both energy and economic aspects, unless useful life of the system does exceed 20 years.

In Cheze et al.,[72] the simulation results of several SAHPs, developed in the framework of an European-funded project (i.e., SunHorizon), are presented. In the first configuration, a new thermally activated CO_2 heat pump integrated with a gas burner is coupled in parallel with high vacuum solar panels for space heating and direct hot water supply (**Figure 8**a). When solar radiation is not enough to supply energy to space heating and direct hot water circuits, the solar circuit delivers energy to the heat pump evaporator. A stratification tank ensures different temperature levels within the storage. This configuration enables direct use of solar energy for the radiator space heating (SH) circuit and DHW solar preheating from accumulated solar energy. In the second configuration, the same layout of the previous one is presented; the high vacuum solar panels are replaced by PV/T panels (Figure 8b). Moreover, when heat production is low, the PV/T heat production supplies energy to the HP evaporator and the excess of electricity production supplies an electrical heater. Both configurations were compared with traditional heating systems equipped with gas boilers and electrical water heaters, the primary energy savings obtained are 36% and 42%, respectively, for the first and second solutions. The presented solutions represent hybrid layouts between the solar evaporator coupling and the parallel one.[73]

A different application for parallel configuration of SAHPs is presented in the study by Hassanien and Tang,[74] where heat is used for a greenhouse, with heating demand at ≈14 °C. For the climate examined, Kumming, in China, it can meet more than 60% of the demand with the exception of December to February, with solar collectors providing more than 35% of the annual required heat for heating the greenhouse and maintaining the nocturnal temperature at 14 °C inside the greenhouse.

The systems discussed in this section are summarized in **Table 4**.

2.5. Solar Source—Solar/Space Heating and Cooling Sink with Mixed Series/Parallel Configuration

The mixed serial/parallel connection configuration for a water source heat pump is shown in **Figure 9**. It consists in the possibility of using the solar collectors both as the main energy provide for space heating or DHW and as evaporator for the heat pump. The variation of the configuration is controlled according to the outlet temperature from solar collectors: if it is compatible with the load heating demand, then solar heat can be directly used. On the contrary, if it is not sufficient for the scope, the thermal fluid of the solar collectors can be used to provide evaporation heat to the heat pump. Such a configuration then allows to keep the advantage of the parallel connection (because it allows to cover part of the yearly demand through solar energy) while making the heat pump working at higher efficiency because the temperature inside the solar collectors is usually higher than ambient temperature.[75] As for the previous cases, it is possible to include in the installation a storage tank. It is, however, worth noticing that this kind of installation requires a more complex management and, as it relies on the connection of only the solar collectors to the heat pump's evaporator, it does not allow for reversible operation in summer, which are instead crucial in many cases to ensure the economic viability of the system.[76,77]

One of the main advantages of this configuration is the possibility of using the heat pump for simultaneous production of DHW and space heating. In order to guarantee the proper operation, however, it is necessary to set a high-temperature output from the heat pump (55–60 °C), which penalizes the COP of the heat pump.[78] A possible solution suggested in Fraga et al.[78] is to use a variable speed heat pump with adjustable set point that can be used with a lower speed and set points when only space heating is needed. The economic viability of the system only for larger scales is also discussed in the study by Dannemand et al.,[79] in which a parametric analysis is carried out to identify the optimal component sizes. The system is composed by PV/T panels, a DHW storage, a buffer storage, and a water to water heat pump. The results indicate that the improved system produces 55% more electricity and has 23% lower electric consumption and wasted 11% less heat by minimizing heat losses. To further improve the efficiency of the system in cold climates, a vapor-injection cycle is proposed in the study by Fan et al.[80] The results indicate that a total renewable-based energy for heating–cooling–electricity of 81.5% can be achieved at cost payback period of 6.52 years and a life-cycle net cost saving of 56328.4 rupees.

Regarding the development of a suitable control logic, a solution is proposed in the study by Banister and Collins,[81] in which a configuration with two tanks is proposed: a tank dedicated to DHW and a "float tank" that can work at different temperature levels. The control strategy implemented establishes priorities of the system modes of operation according to the temperature in the two tanks and at the outlet of solar collectors. Such a strategy allows 12% more energy savings compared to a single-tank configuration, but its additional cost is justified only in a multifamily building context. Another solution that exploits a two-tank configuration to improve the energy utilization and efficiency of the system is presented in the study by Tamasauskas et al.[82] In this

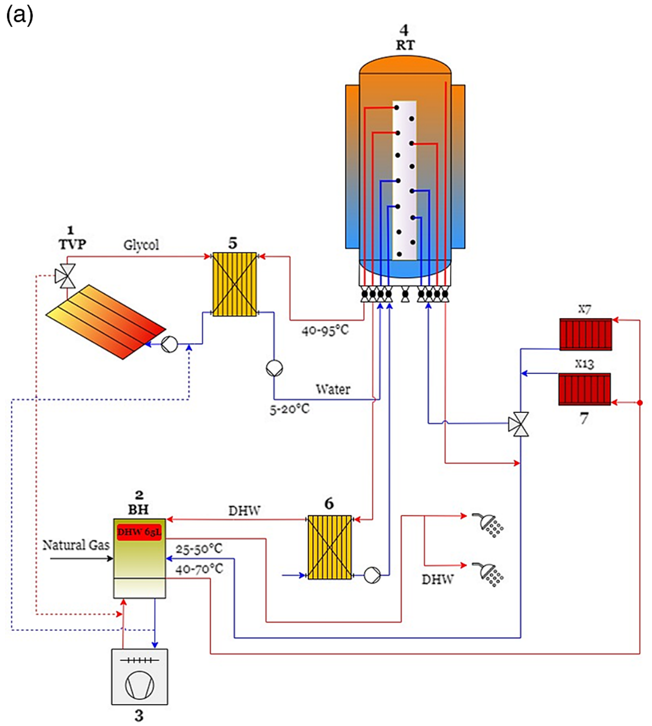


Figure 8. Hybrid configuration (solar evaporator + parallel connection) investigated in the course of the EU-funded SunHorizon project. Coupling with a) high vacuum solar panels and b) PV/T panels.

Table 4. Studies on parallel connection SAHPs.

Solar type	Study	Operation	Solar collector sources	Solar cCollector sinks	HP sources	HP sinks	Refrigerant	COP	Heating/ cooling capacity [kW]	References
ST	E	DHW	Sol	skS	Air	skS	R134a	1.85–2.18	1.51–1.73 CO	[62]
ST	EN	SH, DHW	Sol	srS	Air	skS	–	2.5–7	4.5–5.4 H	[63]
ST	SN	SH	Sol	skS	Air	sKs	–	2.36–4.13	2.55 CO	[64]
ST	E	SH	Sol	SH	Air	HDS, skS	–	2.5–3	1.84 CO	[65]
ST	EN	SH, DHW	Sol	skS	Air	skS	–	2.18–2.63	2.37–2.8 CO	[66]
ST	EN	SH, DHW	Sol	skS	Air	skS		2–5.2	0.2–2 CO	[67]
ST	N	SH	Sol	skS	Air	skS	–	–	–	[68]
ST	N	SH, DHW	Sol	skS	Air	skS	–	3.24–3.79	5.11–6.21 H	[69]
ST	E	SH	Sol	srS	Air	skS	c	2.93–3.22	6 H	[70]
ST	N	SH, SC, DHW	Sol	skS	Air	HDS, CDS, DHWDS	–	–	–	[71]
ST	E	G	Sol	skS	Air	skS	–	4.24	2.79 CO	[74]

case, the solar collectors can be connected to a warm water tank for direct operation for space heating (when the temperature is high enough) or to an ice tank, connected to HP evaporator, where melting heat is exploited to increase the energy storable and therefore increasing the number of hours for solar-assisted operation. Results at the system level show strong energy savings potential up to 66% reduction in heating and DHW primary energy need compared to an electric heater. Moreover, the impact of ice storage on solar collector performance is also clearly evident, with an estimated annual overall collector efficiency of 0.45. The problem of the most appropriate control strategy is a nontrivial one and in refs. [83,84] a methodology is presented, which is based on multiobjective optimization using genetic algorithms where the objectives are the annualized life cycle cost and the comfort-level indoor. The results in different Chilean locations show that SAHP presents significant improvements in performance for almost all locations, reaching the same levels of comfort at a lower cost (which ranges between 400 and 900 $).

The effect of ambient parameters, i.e., solar radiation and ambient temperature on the performance of a SAHP operating

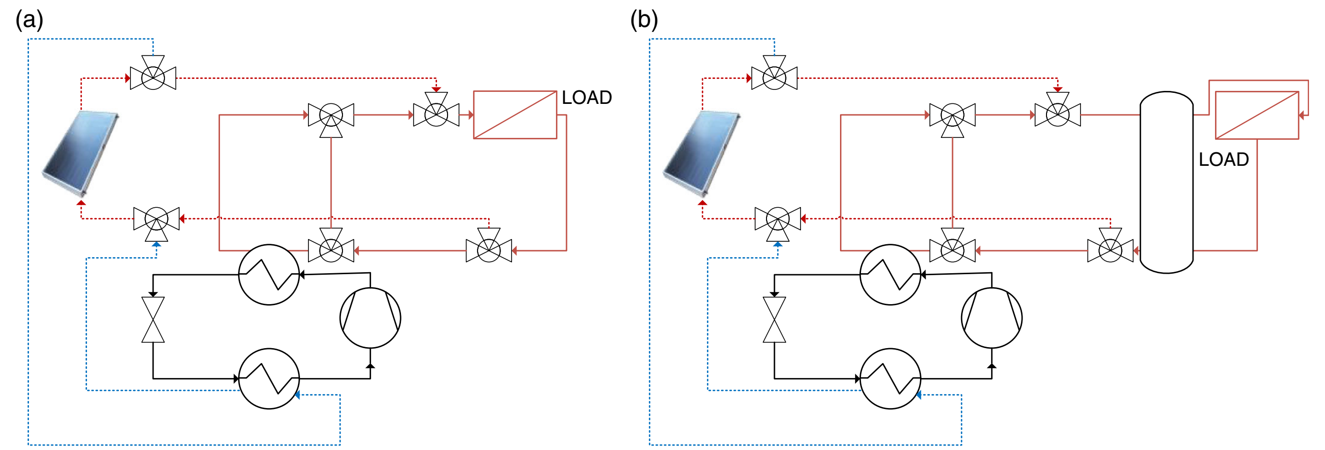


Figure 9. Mixed serial/parallel configuration a) without or b) with storage tank.

under different modes, is discussed in the study by Cai et al.[85] Outcome of the analysis is the identification of the optimal conditions for heat pump operation under the different possible modes (parallel connection, serial connection, or air source heat pump), as presented in **Figure 10**.

The systems discussed in this section are summarized in **Table 5**.

2.6. Dual-Source Configuration

Heat pumps with dual-source configuration are characterized by a mixed series/parallel connection between the solar collectors and the heat pump. At the same time, the evaporator of the heat pump can be connected to an air source unit to use ambient heat or to the solar collectors. This means that, according to the temperature levels, the solar collectors can be used to directly supply heating to the user or to supply evaporation heat to the heat pump. At the same time, the heat pump can use both solar collectors and the air source evaporator, thus allowing also reversible operation during summer and higher flexibility. The configurations in dual source for SAHPs with or without storage on the collectors' circuit are shown in **Figure 11**. The major issue related to this system is the presence of two different heat exchanger (air source and solar/water source) that increases the costs and the control management complexity.

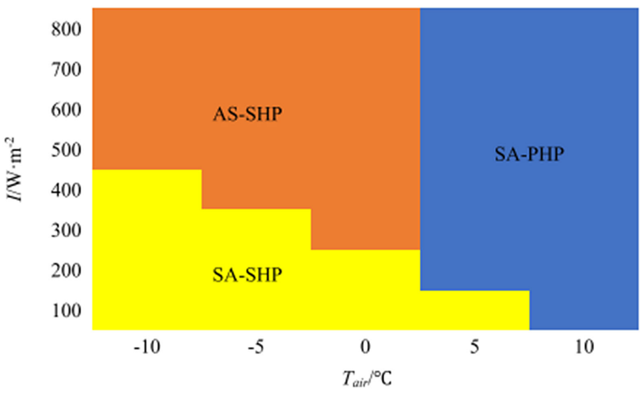


Figure 10. Optimal working condition range for a mixed serial/parallel HP. Nomenclature: AS-PHP, air source serial HP; SA-SHP, solar-assisted parallel HP; SA-SHP, solar-assisted serial HP. Reproduced with permission.[85] Copyright 2022, Elsevier.

This configuration, for its versatility but at the same time challenging management, has been widely studied in the literature. Several analyses focus on the evaluation of the different operating modes for the heat pump, i.e., water–water with evaporation heat supplied by solar collectors or air–water with evaporation heat supplied by the ambient. The effect is particularly significant when the PV/T collectors are used. For instance, in Qu et al.[86] it is found that passing from air operation to water operation, the PV/T panel operating temperature can be decreased up to 45 °C, and the electrical conversion efficiency increases by 10.3%. An extensive experimental analysis on a dual-source system in lab-scale size (approximately 2 kW cooling capacity) is presented in previous studies,[87,88] where the different possible operating modes of the system are presented: air source heat pump (for both heating and cooling), water source heat pump, solar heating through solar collectors, DHW provision from solar collectors, and electricity provision from PV/T. The results indicate that the COP of the heat pump in dual-source mode increases by 36% compared to the air source heat pump and 11% compared to the water source heat pumps. The average thermal efficiency of solar collectors is 35% in winter and 55% in summer and the electric one is about 14%. An alternative configuration for optimization of operation in extremely severe conditions (i.e., very low irradiation) is described in the study by Fang et al.[89] The leading principle is that the thermal energy of waste bath water in buildings is another alternative heat source although intermittent. Accordingly, a system was designed with an additional thermal tank that can collect all the available thermal energy from bathing water and reuse it for space heating when required. The results of an experimental and numerical analysis indicate that energy saving with such a configuration is possible. Another configuration designed to better exploit the dual-source possibilities is presented in the study by Fan et al.[90] and shown in **Figure 12**, based on a modified solar-assisted ejector-compression heat pump cycle (mixed heat pump [MHP]) using the zeotropic mixture R290/R600a. The use of a zeotropic mixture allows employing the separation condensation technique and the ejector can increase the compressor suction

Table 5. Studies on mixed serial/ parallel connection SAHPs.

Solar type	Study	Operation	Solar collector sources	Solar collector sinks	HP sources	HP sinks	Refrigerant	COP	Heating/ cooling capacity [kW]	References
ST	EN	DHW	Sol	srS, skS	Water	skS	–	2.3–6.3	0.9 CO	[81]
ST	E	SH, DHW	Sol, Air	skS, HP	S	HDS, skS	–	2–4	1 CO	[78]
ST	N	SH	Sol	HP	Air, S	HDS	–	4.33–4.58	0.64–0.69 CO	[85]
ST	N	SP	Sol	skS, HP	Air, S	skS	–		0.3–3.1 CO	[83]
PVT	N	DHW	Sol	srS, skS	S	skS	e	R407c	0.67 CO	[79]
ST	N	SH	Sol	sks, HP, SH	S	HDS	e	–	–	[77]
ST	N	SP	Sol	skS, HP	Air, S	skS	–	6.7–8.2	0.9–3.1 CO	[84]
ST	EN	SH, SC	Sol	srS, skS	Air, S	skS	R507a	2.07–2.69	17.8 H	[82]
ST	N	SH	Sol	skS	Air	skS	R22	3.3–5.1	0–3 CO	[75]
ST	N	SH, SP	Sol	skS	S	skS	R22	4.1–4.3	5.7 CO	[76]
ST		SH, DHW	Sol	skS	Air	HDS, DHW	–	2.1–3.6	13.2 CO	[80]

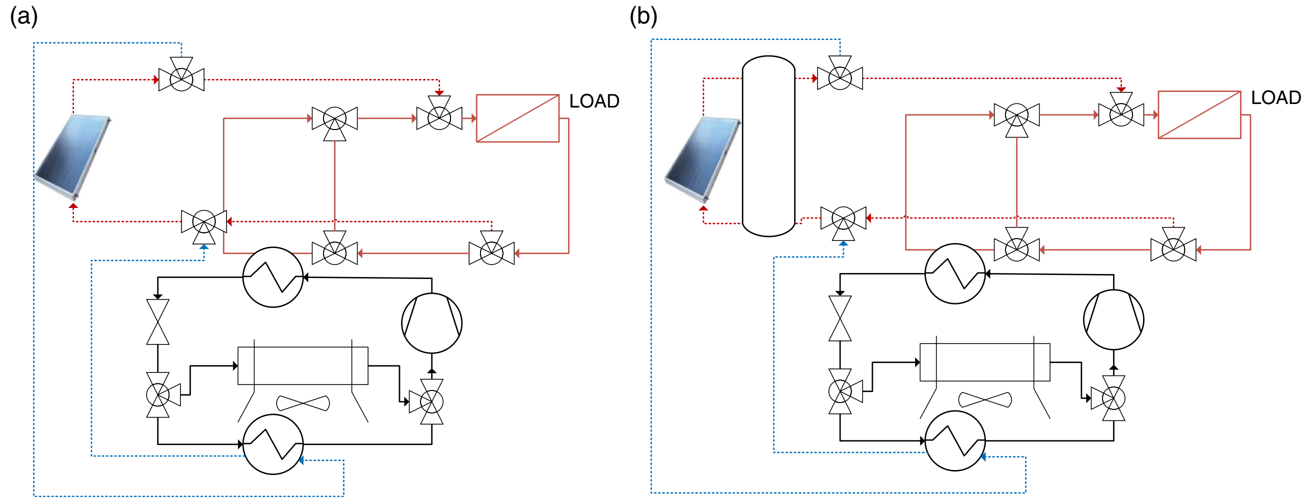


Figure 11. Dual-source configuration a) without or b) with storage tank.

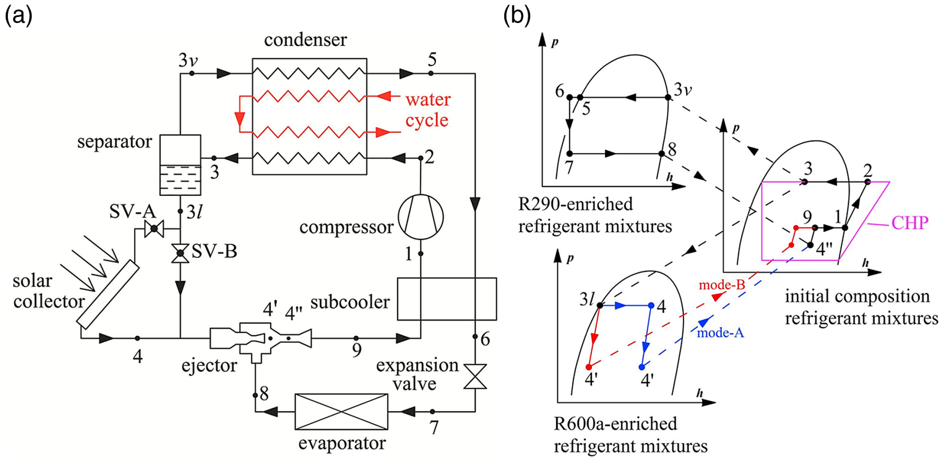


Figure 12. The mixed heat pump-ejector cycle. Reproduced with permission.[90] Copyright 2022, Elsevier.

pressure and reduce the compression work. The results are compared to a standard compression heat pump cycle and it is found that about 30% COP improvement can be achieved at 10 °C ambient temperature.

Research has also been devoted to components to be used in this type of heat pumps. For instance, in Wang et al.[88] a novel evaporator was developed (see **Figure 13**) in which the exchange between refrigerant and solar fluid is achieved by flowing the refrigerant within fins that are fixed on the solar fluids' channels. In Zhang et al.,[91] the innovation is focused on a three fluid heat exchanger that is used for energy transfer in the evaporator of the heat pump. The operation is as follows: during winter, according to the temperature levels, the heat pump evaporator can simultaneously obtain heat from the heat pipe condenser (from solar) and the fins (from air). When heating is not required, excess heat can be dissipated from the heat pipe condenser into the air through the fins. The schematic of the three-fluid heat exchanger is shown in **Figure 14**. The operation of a dual-source heat pumps with two evaporators (one on the solar collectors and a finned tube air source one) is discussed in the study by Cai et al.[92] and the results indicate that their concurrent operation (i.e., in series) is not consistent. On the contrary, the most appropriate strategy is to use the finned tube evaporator with solar irradiations between 50 and 100 W m^{-2}, while for higher solar radiations the evaporator of solar collectors has a better heat transfer capacity and should be preferred. The research described in the study by Ran et al.[41] also proposes a solar evaporator that can work in three modes: solar heat source, air source, or thermosyphon mode to directly provide space heating, thus having a compact installation without losing the advantage of the dual-source configuration. Results of the numerical analysis with this system show that the energy saving rates can reach 48% and 66% compared with air source heat pump and the conventional solar heating system, respectively.

In Liang et al.,[93] the novel component investigated is a roll-bonded PV/T unit that works as an evaporator during heating mode and as a condenser during refrigeration mode. In this way, three possible heat sources are used: solar radiation, long-wave cold radiation, and air. It is tested experimentally in the north of China during summer, exploiting a night/day cycle, using an ice storage for heat storage. The results show that COP varies from 2.4 to 3.5 with an average value of 2.84 and the refrigeration power of unit area of the PV/T unit varies from 0.35 to 0.5 kW with an average value of 0.41 kW m^{-2}, thus demonstrating the good potential of the technology. Some specific configurations were also developed for application with very low ambient temperatures. For instance, in Ran et al.[94] a configuration with multiple heat exchangers on the evaporator side is evaluated, so that when one of these is in defrosting mode, the others can still work to guarantee a continuous heat output. In this way, even for harsh winter conditions, COP higher than 3 can still be achieved and the energy needed for defrosting is only 30–36% of that needed by a standard dual-source SAHP and only 16–35% of a standard air source SAHP.

In Huan et al.,[95] focus is devoted on the optimal strategy to be used in dual-source heat pumps. The results from an experimental campaign indicate that the operation in serial or parallel mode is strongly influenced by ambient temperature and solar radiation within the same day and therefore there is the need to switch operating mode not only on seasonal basis but also within the same day. The switching condition is obtained by solving the equation that calculates heating capacity in serial mode and in parallel mode

$$Q_{\text{serial}} - Q_{\text{parallel}} = 0 \tag{1}$$

By replacing the expressions derived from energy balance equations, such an expression becomes a function of solar radiation and temperature. Accordingly, using the real-time values or the predicted ones (i.e., if a model predictive control is implemented) allows the definition of switching conditions for the optimal operation of the system. Results from annual simulations using such a strategy show that the average COP of

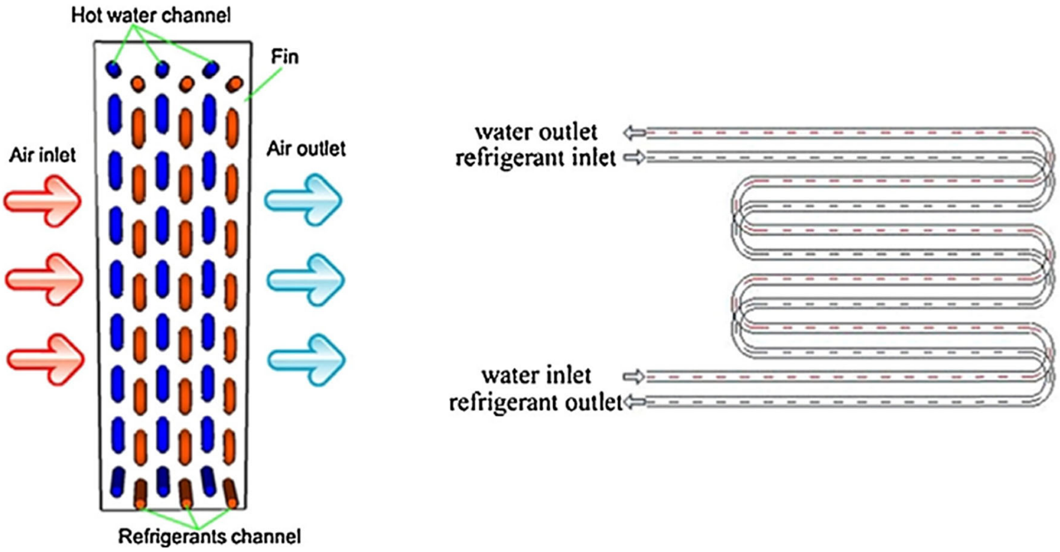


Figure 13. Composite evaporator developed in ref. [88]. Reproduced with permission.[90] 2022, Copyright Elsevier.

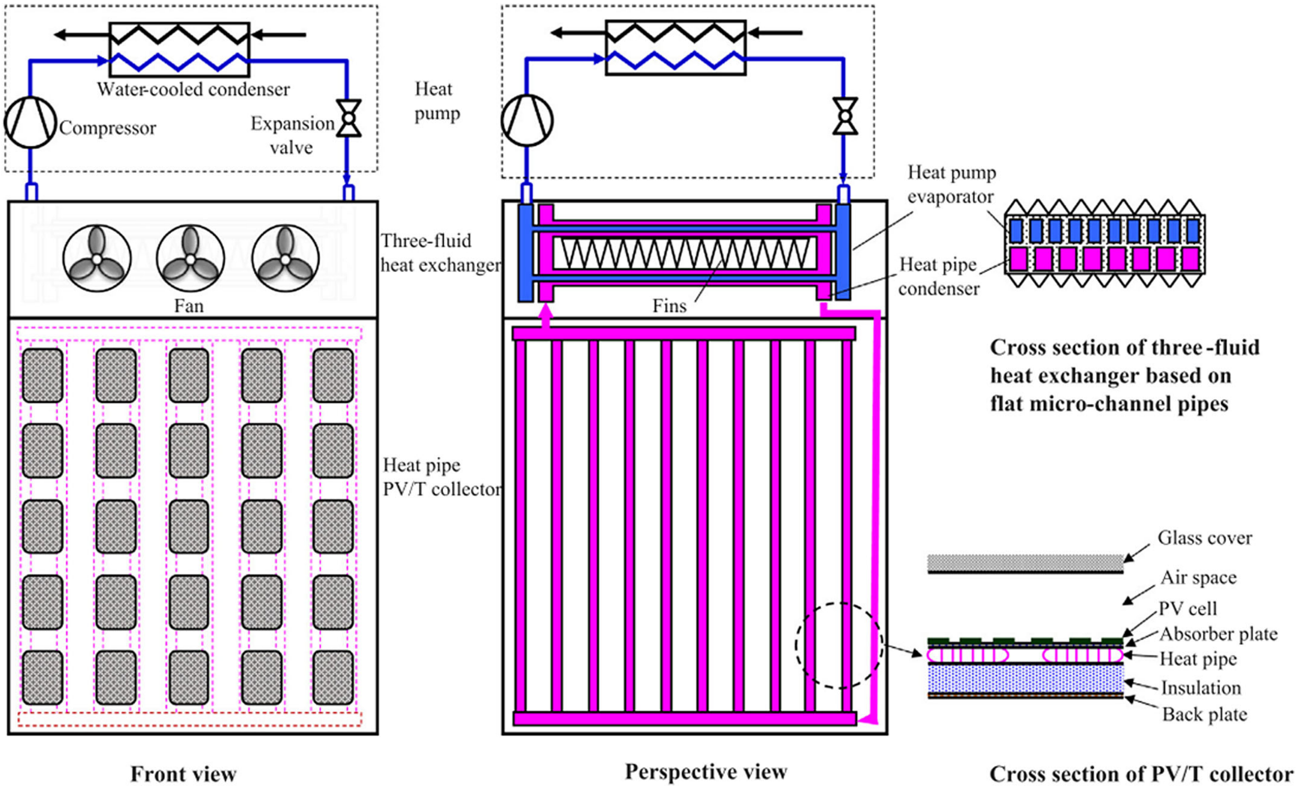


Figure 14. The SAHP with three-fluid heat exchanger developed. Reproduced with permission.[91] Copyright 2022, Elsevier.

dual-source configuration is double compared to the serial one and about 30% higher than parallel configuration.

Another control strategy to match the variation in solar radiation and ambient temperature is proposed in the study by Cai et al.,[96] which consists in varying the mass flow rate of water in the evaporator according to the different temperature demands and heat load. In this way, the effect of variable solar radiation during day on COP of the heat pump is less marked.

Energy-cost saving trade-offs are discussed in the study by Simonetti et al.,[97] where different configurations are compared and the optimal sizing is discussed, using an optimization algorithm based on the mixed integer linear programming technique. The results show that the dual-source heat pump system with the largest battery size is the system that achieves the highest energy savings, i.e., 77% primary energy saving with respect to traditional boiler-based system, whereas the lowest operating cost and the highest economic saving are obtained using the conventional air-to-water heat pump without any electric storage, thus remarking that economic profitability further needs to be addressed.

The studies reported in this section are summarized in **Table 6**.

2.7. Solar-Driven Thermal Heat Pumps and Chillers for Space Heating/Cooling: Technical Aspects

Thermal heat pumps are those that use a thermal compressor instead of a mechanical one, requiring driving thermal energy at a temperature level of ranging from 50 to 120 °C for operation, depending on the specific technology. The two most common technologies are the liquid sorption (i.e., absorption) and the solid sorption (i.e., adsorption),[98] both exploiting the ability of specific materials, i.e., sorbents, to reversibly react with the refrigerant, thus compressing it from the evaporator to the condenser, exploiting thermal energy as driving source. In this case, the heat pump works at three or four different temperature levels[99] and the solar energy source can be used for driving the desorption process or to provide the necessary evaporation heat. The advantage in the use of this configuration is the increased efficiency compared to direct space heating (up to 30% more at low radiations, i.e., below 800 $\mathrm{W\,m^{-2}}$) with considerable savings in terms of primary energy.[100,101] Typical configurations for thermal heat pumps are shown in **Figure 15**. According to the working pair (i.e., specific sorbent and refrigerant pair) and technology chosen, the operating temperature levels can vary significantly and therefore the coupling with solar thermal collectors' technology is highly dependent on the application, as specified in **Figure 16**.

One application of such heat pumps is in cogeneration systems, in order to exploit the waste heat from the cogeneration stage. For instance, in Li et al.[102] an absorption heat pump is used to recover the waste heat from condensate from a solar power plant. In this way, the thermodynamic performance of the solar system is improved from 16.90% to 17.17% and from 15.76% to 16.05%, respectively. At the same time, the unit heating cost decreases from 8.1 to 2.8 ¢ $\mathrm{kWh^{-1}}$ with the increase of

Table 6. Studies on dual-source configuration SAHPs.

Solar type	Study	Operation	Solar collector sources	Solar collector sinks	HP sources	HP sinks	Refrigerant	COP	Heating/ cooling capacity [kW]	References
ST	N	SH	Sol	HP, SH	Air, S	HDS	R410A	3.12–3.89	0.19–0.21 CO	[41]
PVT	E	DHW	Sol	srS	Air, S	skS	R134a	2.6–5.05	0.9–1.1 CO	[86]
PVT	EN	SH, SC	Sol	srS	Air, S	HDS, skS	–	1.6–4.1	0.43–0.61 CO	[87]
PVT	E	SH	Sol	srS	Air, S	skS	R22	1.5–3.3	0.76 CO	[88]
ST	N	SH, DHW	Sol	HP	S	HDS, DHWDS	R290/R600 zeotropic	4.49–5.77		[90]
PVT	N	SH	Sol	skS	Air, skS	HDS	R410A	2.5–4	2.25 H	[91]
ST	N	SH, DHW	Sol	HP	Air, S	HDS, DHWDS	–	4.34–5.75	0.75 CO	[92]
PVT	E	SH, SC	Sol, Air	HP	Air, S	HDS, CDS	R22	2.29–2.84	1.45–2 C	[93]
ST	N	SH, DHW	Sol	skS, HP	Air, S	skS	–	2.5–4.3	125–240 H	[94]
ST	EN	SH, DHW	Sol	srS, skS	Air, S	skS	R417	3.3–4.3–5.7	95 CO	[95]
ST	EN	SH, SC, DHW	Sol	skS, HP	Air, S	HDS, CDS	R22	2–3	0.6–0.9 CO	[96]
PVT	N	SH, DHW	Sol	skS, HP	Air, S	SH, skS	R410A	1.8–4.4	0.2–2.3 CO	[97]

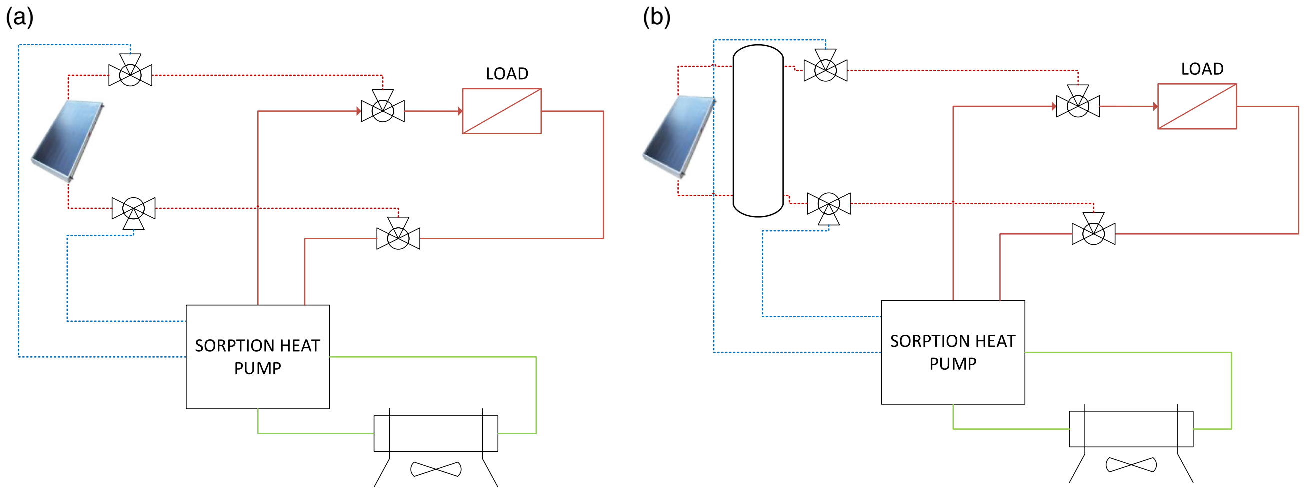


Figure 15. Configuration of solar thermal heat pumps a) without and b) with thermal storage.

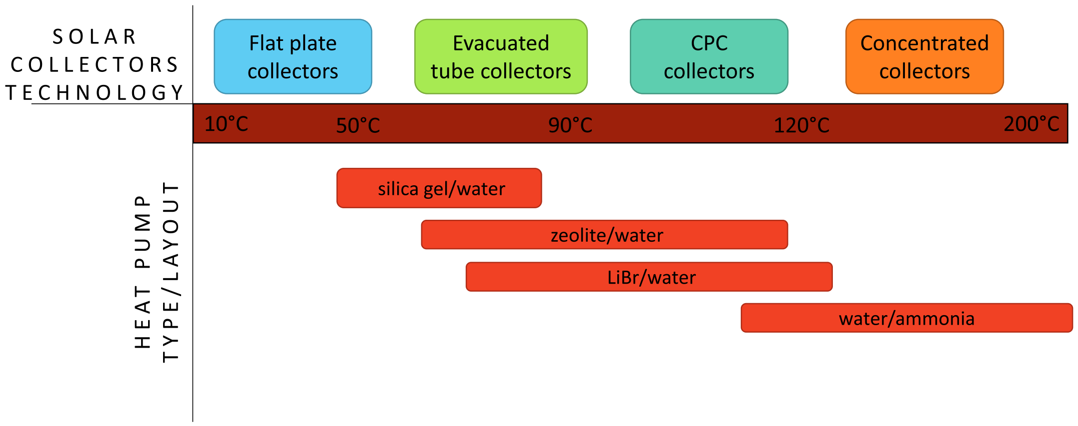


Figure 16. Technology matching between thermal heat pumps and solar system components for commercially available thermally driven systems.

operation time from 228 to 2880 h. Another application in trigeneration systems is the use of waste heat from an Organic Rankine Cycle (ORC) to drive a sorption chiller, described in refs. [103,104], that is analyzed from energetic, exergetic, and financial point of view. The optimal system is found to have heating, cooling, and electricity production equal to 995, 232, and 154 kWh, respectively, with payback period of 5.33 years and the internal rate of return 20.02%, values that prove the feasibility of the system. Another configuration that exploits waste heat for trigeneration purposes is described in the study by Açıkkalp et al.[105] and consists of a solar-driven Stirling engine, chemical heat pump, and absorption refrigerator. Solar energy is used as the main energy source and waste heat rejected by the Stirling engine is utilized by the chemical heat pump and absorption refrigerator. The aim is to improve the efficiency of the overall system, and compared to a single Stirling engine, the maximum power output of the hybrid system increases by 14% and energy efficiency increases by 13%. A multisource and multioutput energy system for heating, cooling, and electricity is presented in the study by Li et al.[106] which includes solar thermal collectors for space heating and to drive an adsorption chiller and a surface water heat pump. Extensive simulations are carried out and a multiobjective optimization is used to select the optimal design, which is a trade-off between the lowest primary energy consumption and the lowest cost. At the optimal point, the solar fraction is 79.8% in winter, 46.4% in summer, the primary energy consumption is 41.68 MWh, and the carbon dioxide emissions are 10.26 tons. A sensitivity analysis highlighted that the capital cost of solar energy and adsorption chillers have the greatest impact on the optimal value of objective function and design parameters, respectively, and then represent the main limiting factor for the economic feasibility of this type of systems. A combined solar heat and power generation system with a solar tower is presented in the study by Li et al.[107] where an absorption heat pump is introduced to increase the overall efficiency of the solar system. Indeed, the proposed configuration increases by almost 5% the efficiency of the system and, at the same time, guarantees a higher adaptability to the variable load (space heating and DHW for residential use).

In order to exploit the features of thermally-driven heat pumps for space heating using low-temperature heat, modified or improved cycles were also developed. In previous studies,[108,109] an absorption–resorption heat pump was developed. Compared to a standard absorption heat pump, the evaporator is replaced by a low-pressure generator and the condenser is replaced by a high-pressure absorber that is used for the resorption process. The advantage in such a configuration is the possibility of lowering the temperature needed from the heat source as well as the inner pressure difference in the cycle. In order to combine the advantages of absorption–resorption heat pumps (i.e., low electricity consumption but weak adaptability to low-temperature ambient conditions) and vapor-compression heat pumps (more reliable and stable heat supply with temperature variations but higher primary energy consumption), a solar-assisted resorption-subcooled compression hybrid heat pump system is proposed in the study by Jia et al.,[110] whose schematic diagram is shown in **Figure 17**. The two cycles realized are connected through a low-pressure generator/subcooler, in which the heat released by the refrigerant subcooling process of the compression subsystem contributes to the low-pressure generation process in resorption one. The effect is to achieve higher heating capacity and adaptability to low ambient air temperature. Results of the thermodynamic analysis indicate a COP_{tot} of 2.41, with primary energy ratio 54% higher than that of the equivalent compression system under the same operation conditions and 35% of primary energy savings compared to a compression system of the same heating capacity. Moreover, heating capacity can be almost doubled.

A system that can gradually switch operation from absorption to compression heat pump mode is presented in the study by Wu and Leung[111] and whose different operating modes are schematically described in **Figure 18**. It is intended to transform operation from an individual absorption cycle to an individual vapor-compression cycle, with many hybrid cycles of different absorption-to-compression ratios in between. Final goal is to increase the flexibility of the system to match the variable solar radiation, ambient temperature, and building load that are encountered in real operation. Results show that for condenser inlet of 25 °C and generator inlet of 90 °C, the cooling capacity drops from 170.3 to 71.0 kW and the cooling COP rises from 7.1 to 38.4 as absorption–compression ratio increases from 0.2 to 0.8. An analysis on solar collectors and most appropriate design is done, showing the potentiality of the hybrid solution.

In Cheze et al.,[112] the simulation results of hybrid sorption–compression chiller coupled with high vacuum solar panels is reported. Solar panels, connected to a stratified tank, supply the driving energy to the sorption unit (**Figure 19**). This delivers chilled water to another storage tank to which the compression chiller is also connected. The system is integrated in serial connection with a reversible heat pump for supplying cooling (in summer) and heating (in winter) to an air handling unit (AHU). In winter operation, if solar energy is enough, the reversible heat pump is not activated. This system was compared with a reference one composed only by a reversible heat pump; results show an overall primary energy saving ratio of 33.4% for both annual operations.

The studies discussed in this section are summarized in **Table 7**.

3. Use of Solar-Assisted Heat Pumps in Other Applications

3.1. Food Driers and Water Treatment

The need for treating water for civil uses and the use of dryers for food preservation are a priority in several regions[113] and the use of SAHPs can further increase the productivity of these technologies.

Purification of water using a heat pump-assisted solar still is discussed in the study by Khaoula et al.[114] In a standard solar still, the incident solar radiation is transmitted through the transparent glass cover of thermal collector to the water that evaporates. In a heat pump-assisted system, a heat pump is added, whose condenser is immersed in the water bath, in order to increase the temperature and therefore the amount of water evaporated, with an increase of more than 20% in overall efficiency of the process. The evaporator of the heat pump is placed

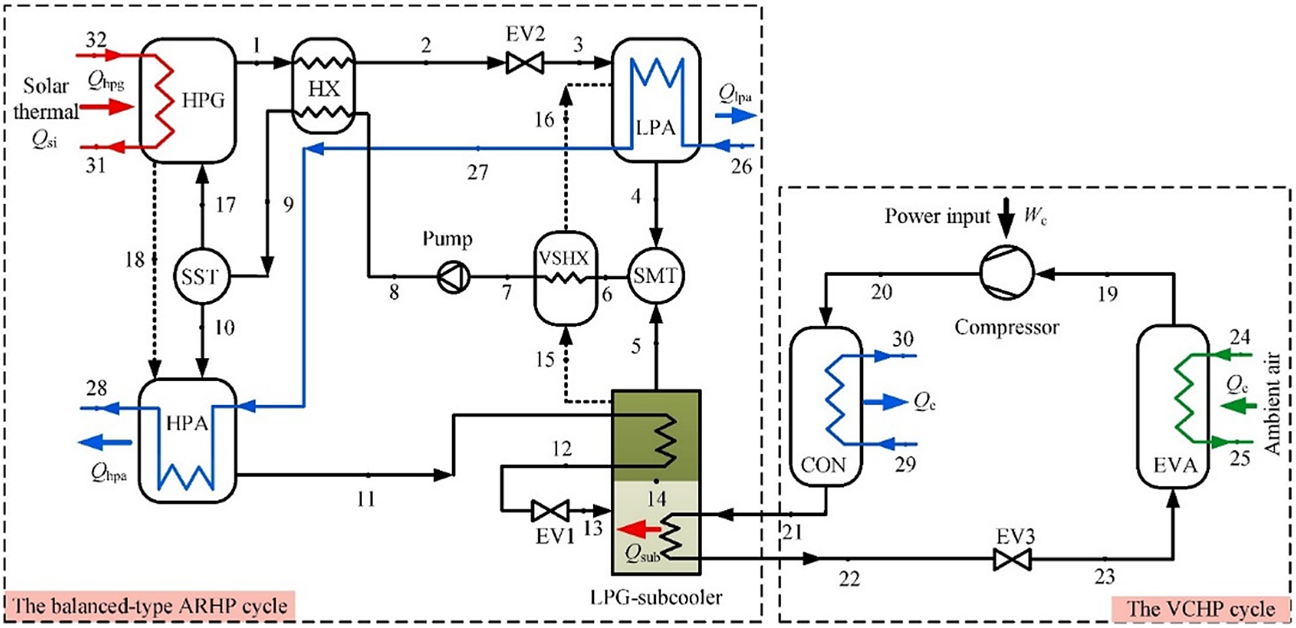
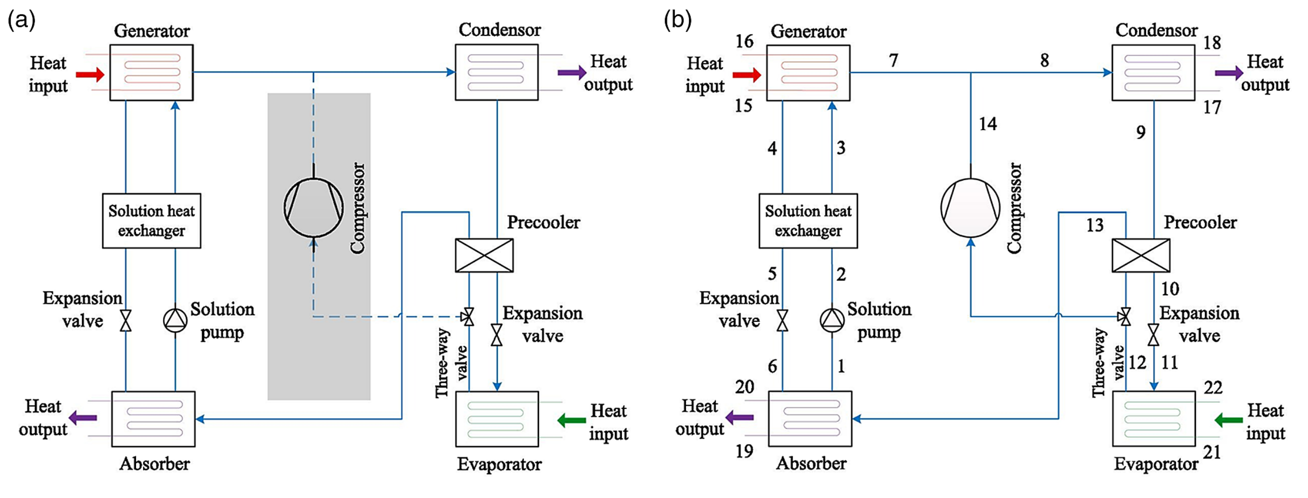


Figure 17. Schematic diagram of the resorption–compression system for space heating proposed. Reproduced with permission.[110] Copyright 2022, Elsevier.

in the upper part of the solar collector, in order to further increase heat exchange due to convection. An experimental campaign to evaluate energy and exergy efficiency of the configuration is presented in the study by Akrout et al.[115] Results indicated about 40% improvement in energy efficiency with heat pump-assisted active solar still compared to the conventional passive solar still. Similarly, the exergy efficiency increases from 8% (for the passive solar still) to 20% (for the heat pump-assisted one). In order to increase the efficiency and operational hours of this kind of systems, it is proposed in the study by Belyayev et al.[116] to use a latent heat storage for solar energy storage. Another configuration for a membrane-based distillation unit is presented in the study by Ma et al.[117] and shown schematically in **Figure 20**. In this layout, brine water is sent to a flat plate collector-vacuum membrane module. The vacuum pump is used to maintain the low pressure on the permeate side, thus allowing for a considerable permeation also at low feed temperatures. The heat pump is used so that the latent heat of evaporation is taken from the permeate at the cold source and recovered back to the hot source to heat the recirculation flow. In this way, it is possible to increase the water production and reduce electricity consumption for the membrane distillation.

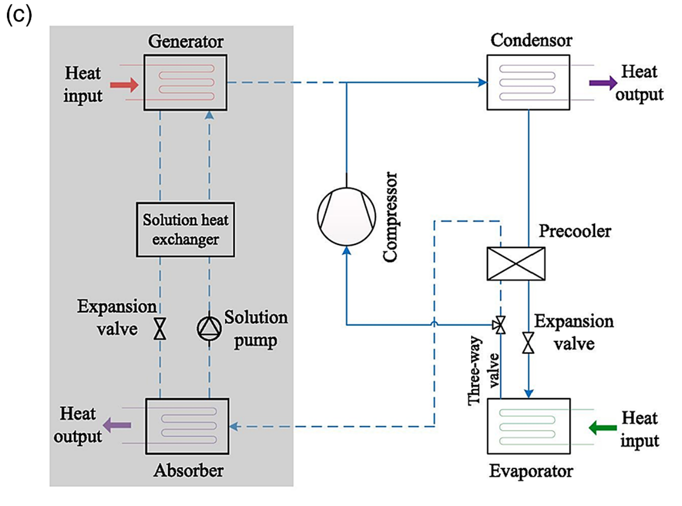
SAHPs can also be used in thermally driven desalination processes. For instance, in refs. [118–120] an extensive numerical and experimental study is carried out on a desalination system with internal heat recovery based on humidification–dehumidification process. In this case, the heat pump cycle is utilized for providing a heat source to hot seawater cycle and a cold source to process air cycle. The process air cycle is used as a carrier of water vapor to achieve the process of humidification–dehumidification. Compared with the single-stage humidification desalination system, the system productivity and corresponding gained output ratio are increased by 15.51% and 55.64%, respectively, due to the favorable operating conditions.

Food preservation through drying using SAHPs has also been investigated in recent years. An application in a cogeneration system applied in China is presented in the study by Han et al.[121] In this case, two SAHPs are used, in which solar energy is used to increase the temperature at the evaporator and therefore has a higher output on the condenser side, to guarantee the efficient drying of food. In the case of the solar-assisted dryer for banana chips experimentally tested in the study by Singh et al.,[122] the solar collectors are installed in series after the outlet of heat pump condenser and prior to the entrance of the drying chamber, in order to increase the temperature of the air used for drying purposes. The effect of using the SAHP compared to a drying system completely relying on coal burning is a much higher moisture extraction rate and a lower drying time. In Wang et al.,[123] the configuration proposed for mango drying is structured in order to operate independently in solar drying mode and heat pump drying mode, or to operate in a joint mode. The schematic layout and operational logic are shown in **Figure 21**. The evaporator of the heat pump and a heat exchanger are used to have a further heat recovery from the exhaust moist air from the drying chamber and thus increasing the utilization of energy. The efficiency of the solar-assisted drying mode is 6% higher than the heat pump drying mode, with a COP of 3.69. In Khouya,[124] a hybrid system for wood drying is presented, in which the heat produced by a heat pump and the thermal energy extracted from PV/T collectors are collected in parallel and stored in a water tank. This is, in turn, connected to a water/air HEX to heat up the air entering the drying chamber. According to the developed model, the combined use of the heat pump and a PV/T system has the effect of reducing the electrical energy consumption ratio by 39% and 86%, in January and July,



AHP mode

HEHP mode



EHP mode

Figure 18. Different operating modes of the flexible heat pump developed. Reproduced with permission.[111] Copyright 2022, Elsevier.

respectively. A fluidized bed for rice drying is presented in the study by Yahya et al.,[125] where economic feasibility of the system is investigated. The system was able to efficiently reduce moisture content from rice with payback period lower than 3 years. A different case is instead presented in the study by Kuan et al.,[126] where a drying system is developed for continental climate. In these conditions, due to low solar irradiation availability, an SAHP heat pump in series configuration is used to maintain the required drying temperature in the drying chamber when solar heat is not available. Results from the study indicate that the specific moisture extraction rate and COP of the system are about 0.6 kg kWh^{-1} and 2.72, respectively.

Air treatment through SAHPs is used also for air conditioning applications, apart from food processing. A hybrid solid desiccant cooling system is presented in the study by Luo et al.,[127] which combines a solid desiccant unit and a vapor compression unit. The schematic is shown in **Figure 22**. In this system, the solar-heated water is used as an additional heat source for the regeneration process, together with the heat from the condenser of the heat pump. The experimental results show approximately 10% performance increase compared to the nonsolar alternative. A 2 year experimental campaign on a combined desiccant heat pump system is discussed in the study by Frein et al.[128] The operation of the system is as follows: during cooling season (summer), the HP cooled the supply air and preheated the regeneration air (when dehumidification was needed) while the rest of the regeneration thermal energy was provided by solar energy. During the heating season, if needed, a heating coil heated the supply air using thermal energy drawn from the solar tank, the HP, or the backup heater. With this specific design, it is possible to achieve high air quality, simpler control process, and low electricity consumption for partial load conditions. In Tian and Su,[129] a hybrid system is proposed, consisting of PV/T collectors, heat pump, and desiccant wheel for air conditioning and

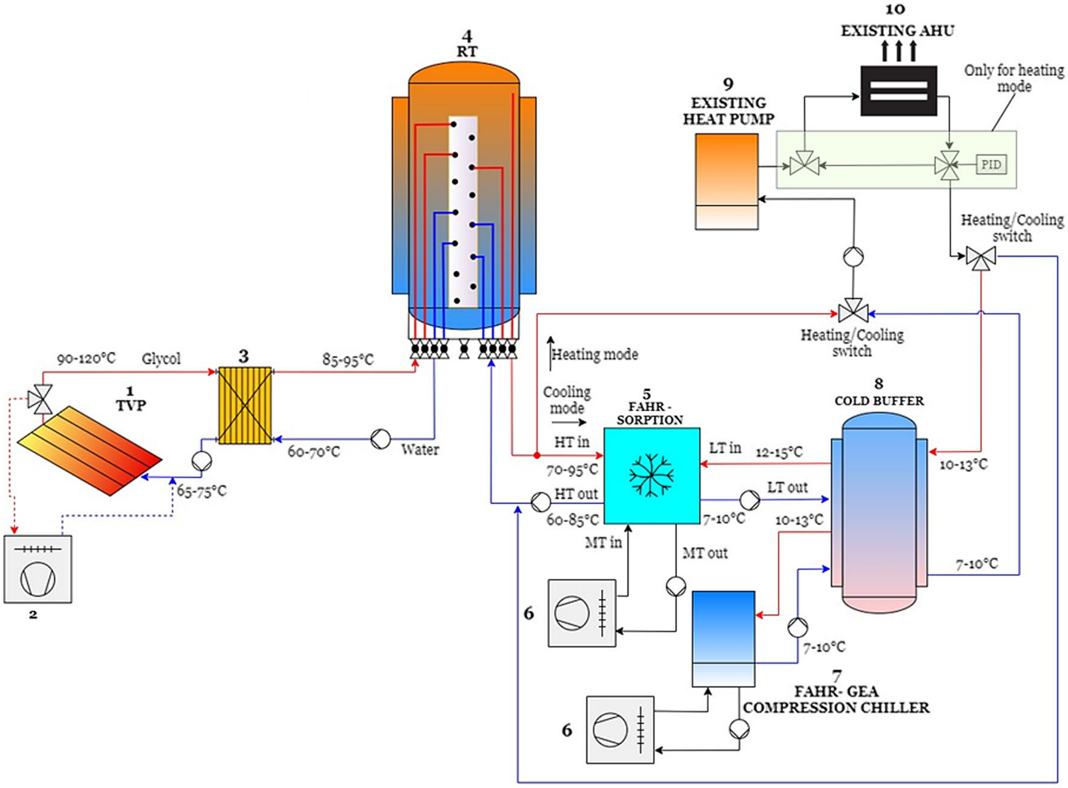


Figure 19. Coupling between high vacuum solar panels and sorption chiller proposed in the EU-funded SunHorizon project.

Table 7. Literature studies on solar-assisted thermal heat pumps.

Solar type	Study	Operation	Solar collector sources	Solar collector sinks	HP sources	HP sinks	Refrigerant	COP	Heating/cooling capacity [kW]	References
ST	N	SH, DHW	Sol	skS	Air, skS	HDS, DHWDS	Water/ammonia		–	[100]
ST	N	COG	Sol	Turbine	Turbine	HDS	LiBr/water	–	–	[102]
ST	N	SH	Sol	skS	ORC, S	HDS	LiBr/water	–	6 kW electricity, 25 kW heating, 24 kW cooling	[103]
ST	N	SH, SC	Sol	skS	ORC	HDS, CDS	LiBr/water	–	413 kW cooling, 947 kW heating, 147 kW electricity	[104]
ST	N	SH, SC	Sol	skS	skS	HDS, CDS	Silica gel/water	0.5	50 kW cooling, 100 kW heating	[106]
ST	EN	SH, DHW	Sol	CHP	CHP	HDS, DHWDS		16% efficiency	70–169 heating	[107]
ST	N	SH	Sol	HP	S	HDS	Water/ammonia	1.153–1.550	–	[108]
ST	N	SH	Sol	HP	S	HDS	Water/ammonia	1.153–1.550	–	[109]
ST	N	SH	Sol	ABSORP	Air	skS	Water/ammonia–R134a	2.41	20–100 kW	[110]
ST	N	SH	Sol	skS	Air	HDS	–	–	–	[111]
ST	E	SH, SC	Sol	srS	Air	HDS, CDS	LiBr/water	2.74–3.3	66 H	[101]

humidification/dehumidification of water. Compared to a traditional air conditioner, the hybrid system can provide a more comfortable thermal and humid indoor environment, with up to 17% energy saving.

The studies presented in this section are summarized in **Table 8**.

3.2. Innovative Configurations Exploiting SAHPs

Apart from the configurations presented in Section 2, the flexibility of SAHPs allows for the application in different layouts and coupled with other generation sources. This includes the cases in which the electricity needed to operate the compressor of the heat

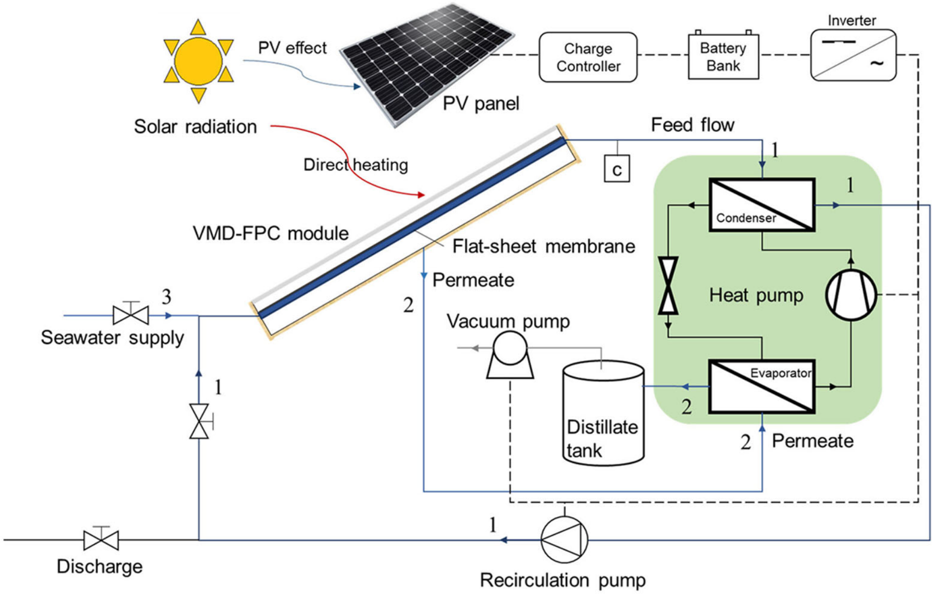


Figure 20. The solar-assisted distillation system with membrane and heat pump described. Reproduced with permission.[117] Copyright 2022, Elsevier.

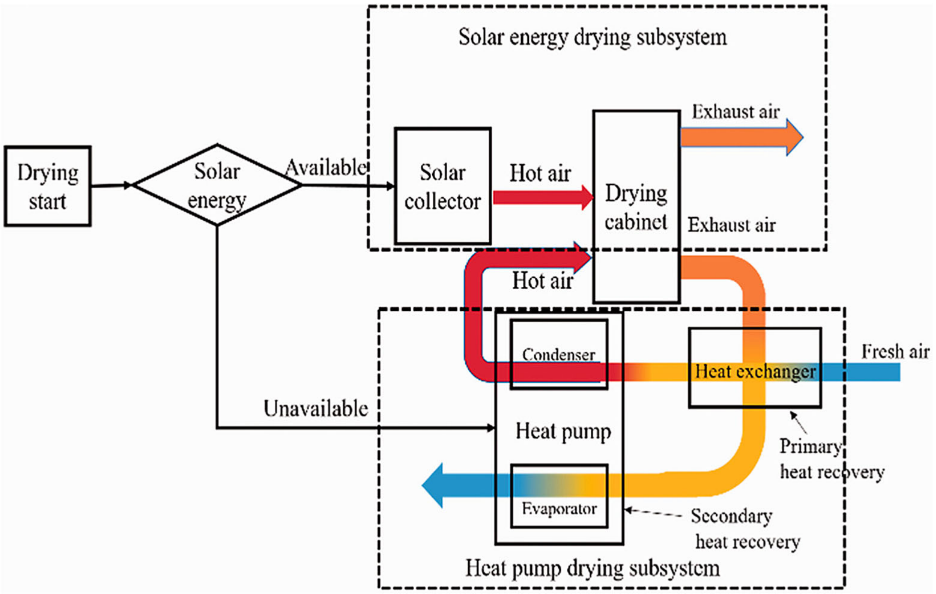


Figure 21. Mango drying system. Reproduced with permission.[123] Copyright 2022, Elsevier.

pump is produced by, e.g., ORC, fuel cells or other combined heat and power systems. An application that is gaining interest is the possibility of having a reversible heat pump/ORC, where it is possible to switch between the operation as heat pump for space cooling or ORC for the production of electricity. This concept is presented in the study by Wu et al.[130] and represented schematically in **Figure 23**. A similar system is proposed in the study by Palomba et al.[131]: solar heat is used as source for the evaporator of a reversible heat pump/ORC for providing space heating (heat pump mode) or electricity (ORC mode) to increase the flexibility of the system in different climates and building typologies. A dynamic model for a reversible HP/ORC is also developed in the study by Dumont et al.[132] and used for a technoeconomic analysis. Results show that using the HP/ORC unit can turn a single-family house into a positive energy building under favorable conditions that for the case studied are a 138.8 m^2 solar roof in Denmark.

A more complex system with multiple generation sources and multiple outputs is analyzed in the study by Razi and Dincer[133] and shown in **Figure 24**: the system includes a parabolic trough solar collector, a Brayton cycle, a reheat Rankine cycle, and a heat pump based on two thermal energy storage tanks to produce

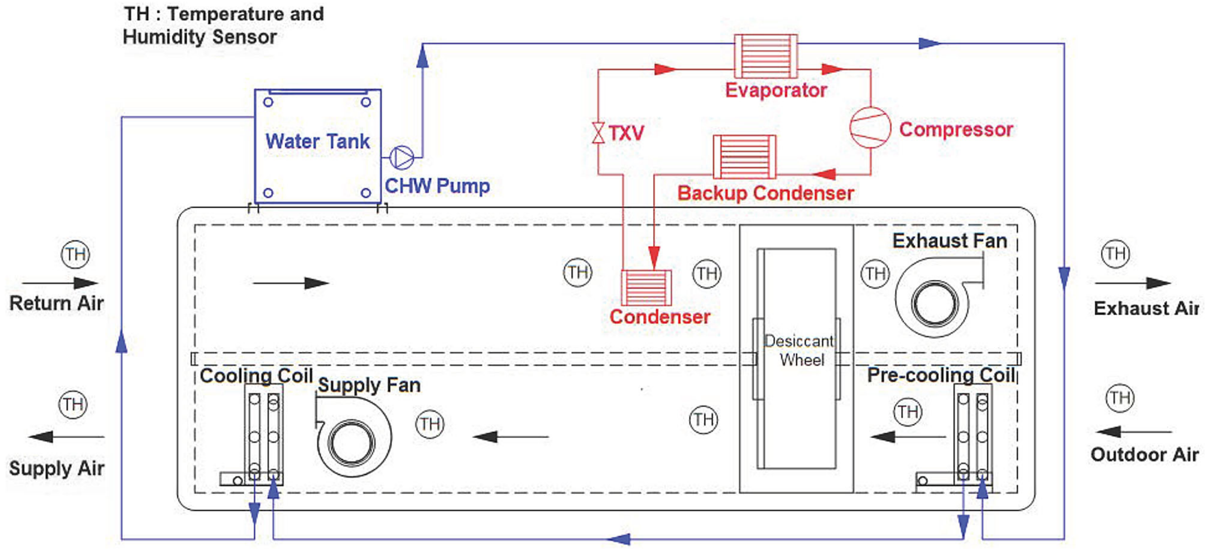


Figure 22. The hybrid desiccant heat pump system. Reproduced with permission.[127] Copyright 2022, Elsevier.

Table 8. Studies on water and air treatment with SAHPs.

Solar type	Study	Operation	Solar collector sources	Solar collector sinks	HP sources	HP sinks	References
ST	EN	Distillation	Sol	skS	Air	skS	[114]
ST	E	Drying	Sol	skS	Air, S	skS	[115]
ST	N	Drying	Sol	skS	Air, S	skS	[116]
ST	N	distillation/ desalination	Sol	Desal, HP	S	Desal	[117]
ST	N	Desalination	Sol	Desal	Desal	Desal	[119]
S	E	Desalination	Sol	Desal	Air	Desal	[120]
ST	N	Drying	Sol	HP	S	Dry	[121]
S	E	Drying	Sol	Dry	Air	Dry	[122]
ST	E	Drying	Sol	Dry, HP	Air, S	Dry	[123]
PVT	N	Dry	Sol	Dry	Air	Dry	[124]
ST	E	Drying	Sol	Dry	Air	Dry	[125]
ST	N	Drying	Sol	Dry	Air	Dry	[126]
ST	E	Drying	Sol	sKs	Air	Dry	[127]
ST	E	SH	Sol	HP, AHU	S, AHU	AHU	[128]
ST	N	Drying	Sol	skS	Air	skS	[129]

cooling, heating, hot water, electric power, and hydrogen. Electric power is produced by the Brayton cycle and the reheat Rankine cycle, hydrogen is produced using a proton-exchange membrane (PEM) electrolyzer, whereas a SAHP produces heating and cooling. Hot water is produced by two sources which include condenser of the reheat Rankine cycle and solar-assisted heat pump. Solar thermal energy is also utilized in preheating the water, which is used as the working fluid in the reheat Rankine cycle. An AHU along with an energy recovery ventilator (ERV) is used for conditioned air. A thermodynamic analysis of the system was carried out, and the overall energy efficiency estimated was 52% while the exergy efficiency is 42%.

Another multigeneration and multioutput solar system is investigated in the study by Yilmaz et al.,[134] which is intended for heating, cooling, drying, hydrogen, and power generation. A schematic layout of the system is shown in **Figure 25**. The main source for the power, heat, and hydrogen generation is solar energy, which is harnessed through a parabolic dish solar collector. Electricity is produced through a Rankine cycle and an organic Rankine cycle; hydrogen is produced using a PEM electrolyzer in cascade to the condenser of the Rankine cycle. Heating/cooling and drying are obtained from a double-effect absorption cooling, dryer, and heat pump. Different operating parameters are investigated to identify the energetic and exergetic performance of integration system. Thermodynamic analysis result outputs show that the energy and exergy performance of overall study are 48.19% and 43.57%, respectively.

These studies further indicate the feasibility of the heat pumps coupled to solar collectors as a means to efficiently provide different outputs for user needs that cover applications in residential, industrial, and civil sectors.

4. Critical Analysis of SAHPs Applications

4.1. Solar Collectors–Heat Pumps Coupling

The research studies presented have highlighted the flexibility of the heat pumps–solar collectors coupling for covering different types of energy demands for residential, industrial, and agricultural applications. A schematic synthesis of the different solar collectors and heat pump layouts for the applications considered is shown in **Figure 26**, where an average value for the available efficiency is presented as well. Based on the literature analysis carried out, the following considerations can be made.

Coupling a heat pump to flat plate solar thermal collectors or, at higher latitudes, to evacuated tube collectors, allows exploiting solar heat as heat source for the evaporation of the heat pump. This reduces the operating temperature lift, thus increasing the

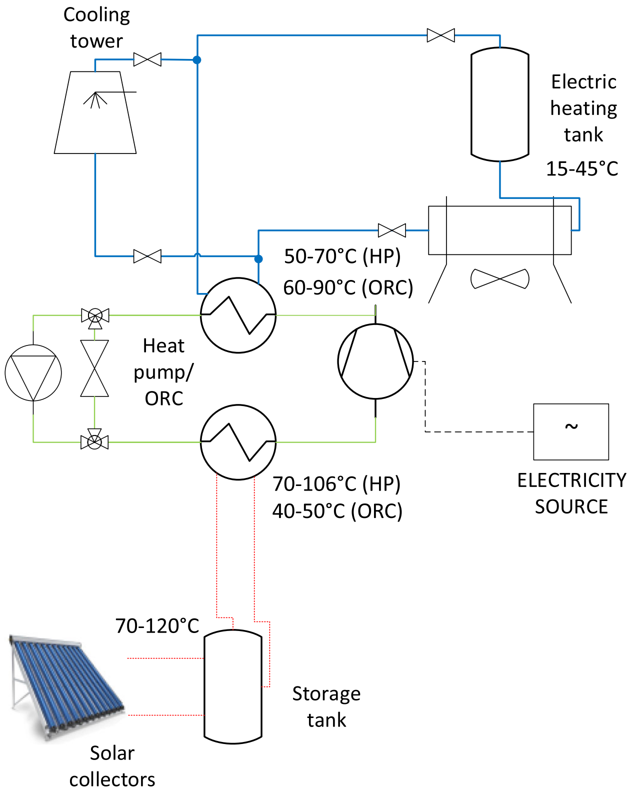


Figure 23. Solar-assisted reversible heat pump/ORC.[130]

overall heat pump performance. This can be done both for low-temperature heat pumps (i.e., evaporation temperature between 5 and 20 °C) and high-temperature heat pumps (i.e., evaporation temperature between 30 and 60 °C). A further distinction can be done between direct expansion and indirect expansion systems. Direct expansion SAHPs have a simpler layout and less components but, on the other hand, their control and stable operation is more difficult and is therefore preferred mainly for smaller sizes.

Connection of the solar collectors on the condenser side of the heat pump is generally done with three purposes: provision of both space heating and DHW with the same system; increasing of the overall efficiency of the system and reduction of emissions, due to the exploitation of solar energy; provision of high-temperature process heat for industrial processes. In case of serial connection, flat plate collectors are generally used because the temperature level is then increased by the heat pump itself, whereas for parallel connection all nonconcentrating technologies are suitable. Instead, for high-temperature heat pumps for industrial purposes, only concentrating solar technologies can be operated in parallel to the heat pump.

Another possible application is the exploitation of solar energy as driving source for sorption heat pumps, for winter applications (thus working as heat amplifiers) in tertiary and industrial buildings, or for summer application, therefore for solar cooling. The temperature level for this application ranges from 90 up to 150 °C, in line with operation with concentrating solar collectors and high-efficiency evacuated tubes collectors and CPC collectors, according to the sorption technology chosen.

Solar-assisted drying and desalination operation is possible, and this is mainly achieved using low-cost collectors, mainly flat plate (for drying purposes) or evacuated tube ones (for desalination purposes), which, compared to solar-only operation, allows much higher production rate and avoids problems, e.g., night stagnant humid air in dryers, that can ruin the crops.

The energy flows connected to heat pump operation, to better highlight the efficiency of the different components, are reported in **Figure 27**, where it is further remarked that the higher COP and better utilization of solar energy are associated with dual-source heat pumps, followed by parallel connection with solar collectors on the condenser side. However, it is worth remarking that this occurs at the expenses of a higher complexity and investment cost of the system and a more difficult control management.

4.2. Overall Suitability of SAHPs in Different Climates and Conditions

In Section 2, the main technical aspects and possible options to deploy solar-coupled heat pumps systems were deeply reported, also referring to the most recent literature. Nevertheless, it is obvious that in order to make them as viable solutions on the market, besides the technical background, also other aspects need to be carefully considered. Recently, an interesting analysis performed in the framework of the EU-funded project SunHorizon proposed a detailed approach to estimate the suitability of SAHPs, considering climatic, building, and market conditions, as reported in ref. [135]. The analysis was carried out exploiting EU-wide data sources and focusing on each national context, trying to cover residential and tertiary sector. Of course, the analysis was generically addressing the potentiality of coupling these technologies without analyzing in details specific technological integration aspects. Accordingly, the proposed methodology, starting from quantitative data, tried to assess the solar-coupled heat pump potentiality in each EU country defining some qualitative classes, clustered in low, medium, and high grade.

Regarding the aspect related to the solar availability, the selected parameters for the analysis are the global irradiation ($\mathrm{kWh\,m^{-2}}$), calculated on annual basis. It allows estimating the potential energy production in terms of electricity and/or heat, given the specifications of the chosen solar technology (photovoltaic, solar thermal, or hybrid). Starting from the data provided by a PV-GIS tool, the potentiality was clustered reporting the country-specific classification of **Figure 28**.[135]

The second investigated aspect is the energy demand for residential and tertiary sector in European countries. The final energy demand can be assessed considering the overall demand of the country for heating and cooling (H&C) as well as defining an average specific demand per built-up area. While the former one is relevant to identify the main countries affecting the overall consumption, the latter one allows also to give an estimation of the energy efficiency of the existing building stock in each country. Data for the analysis were retrieved from EU projects[136] and Eurostat databases.[137] The obtained classification, following this approach, is represented in **Figure 29** and **30** for overall and specific consumption, respectively.

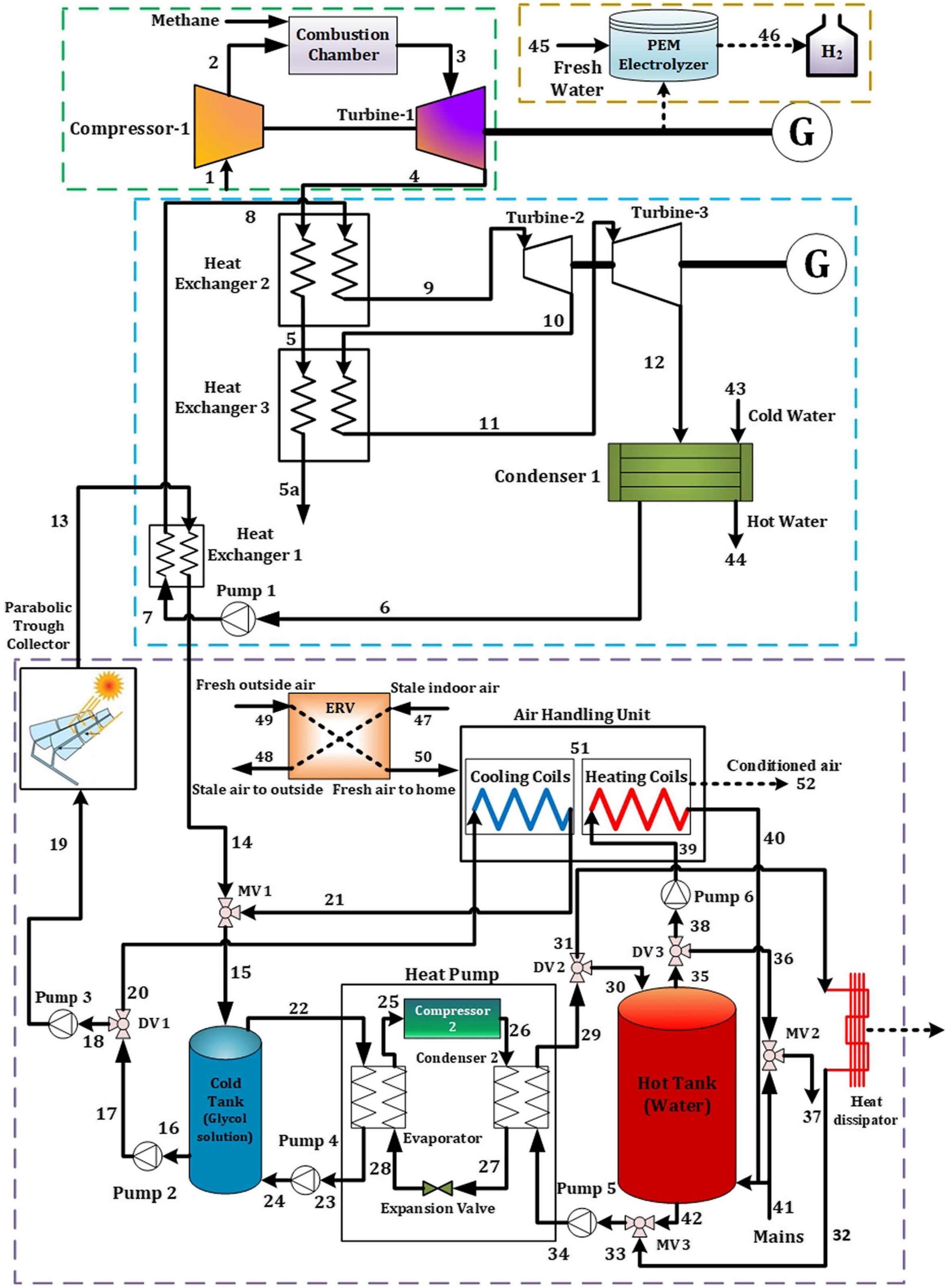


Figure 24. The solar combined cycle integrated with heat pump system. Reproduced with permission.[133] Copyright 2022, Elsevier.

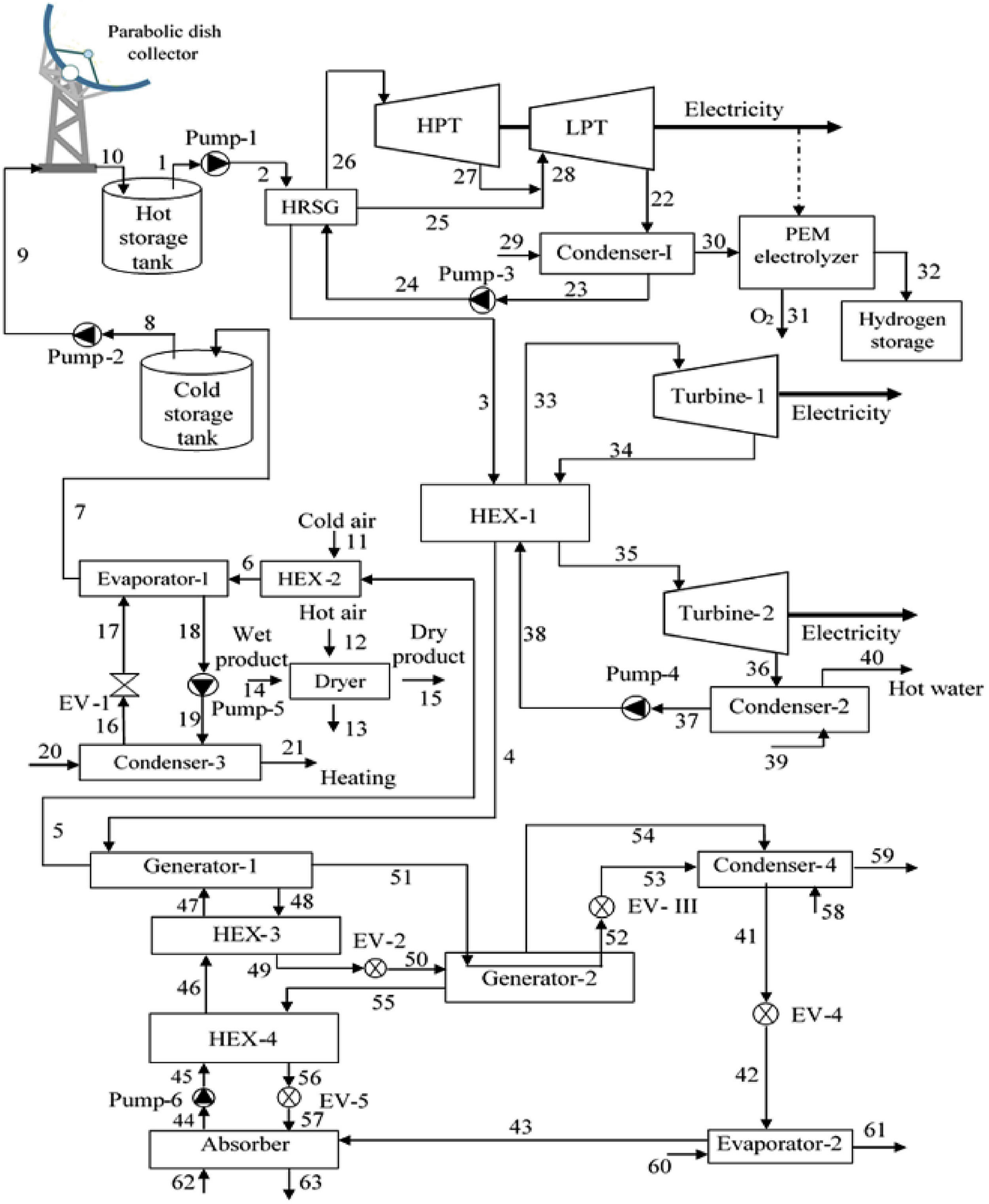


Figure 25. The multigeneration system proposed. Reproduced with permission.[134] Copyright 2022, Elsevier.

In order to assess also the market-related aspects of the SAHPs, the identified indicators were the energy cost and the incentives supporting schemes put in place across the EU.

For what it concerns the energy cost, it is considered as a primary factor because it can be a driver for a higher willingness to invest in innovative and alternative systems by the countries characterized by the higher energy cost. The main energy vectors for heating and cooling (i.e., electricity, natural gas, oil and district heating) were considered in the cost analysis. Both country-specific and average EU costs were considered, allowing to evaluate a qualitative distribution of the costs across the EU for heating and cooling purposes, as shown in **Figure 31**.

The second aspect investigated regarding the market analysis was the presence of subsidies supporting renewable-based approaches like the SAHPs.[137] An analysis must be performed at country level because these subsidies (e.g., price-based support, loans, tax benefits) vary a lot across the EU. Most of them are still mainly supporting electricity generation, so, despite the

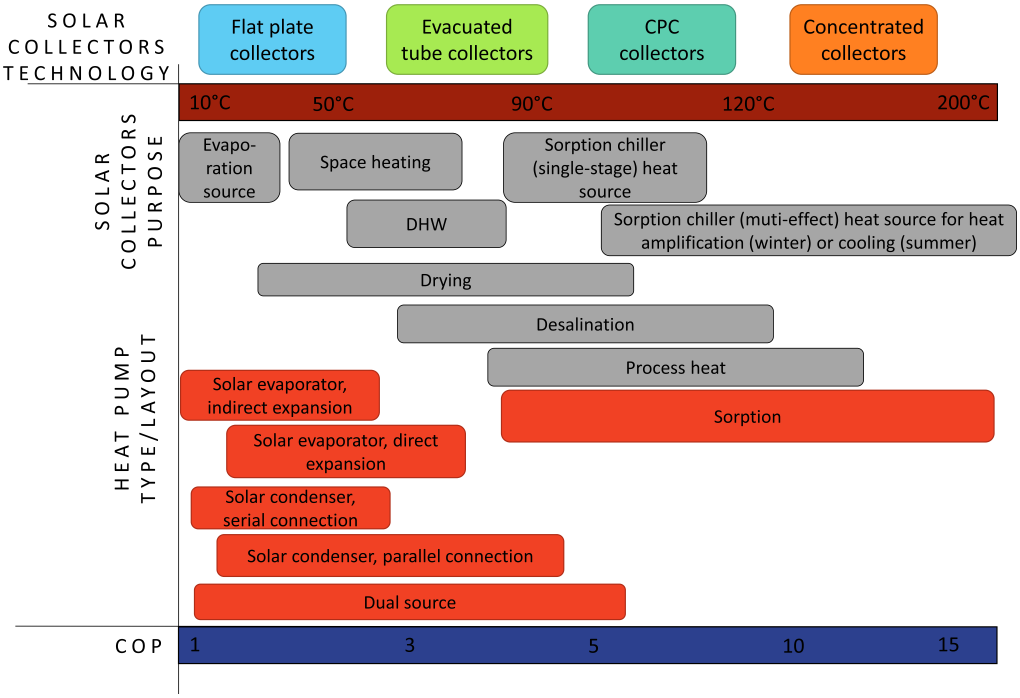


Figure 26. SAHPs: classification according to solar collectors, temperature levels, heat pump layout, and COP.

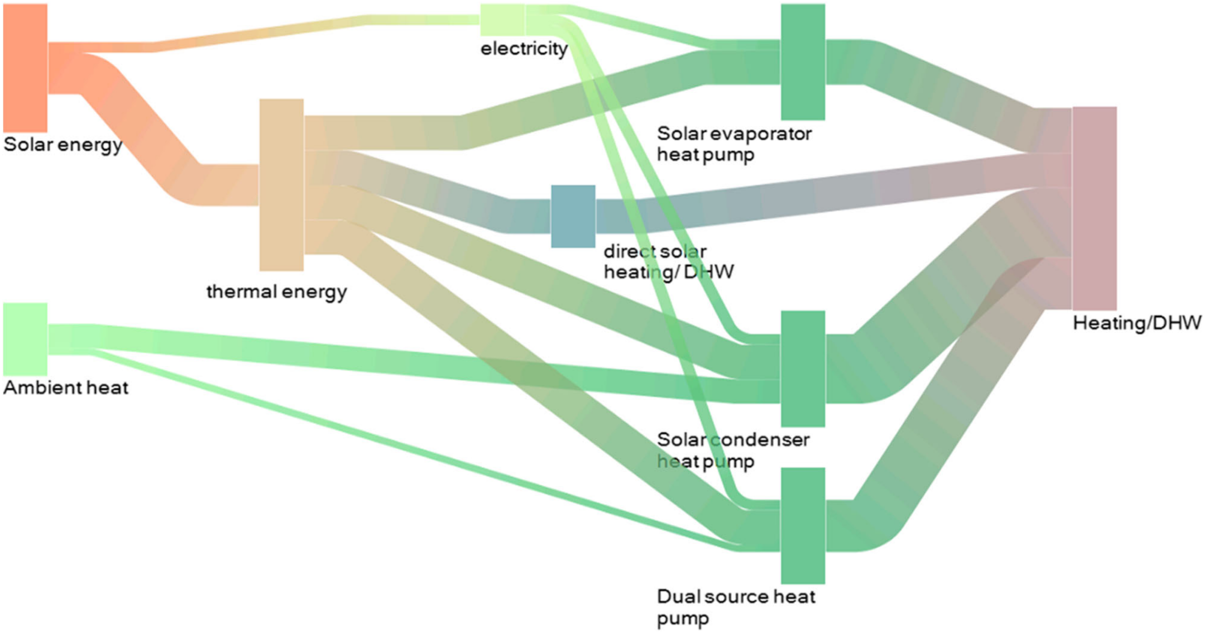


Figure 27. Energy flows associated with SAHP operation.

summary is the one reported in **Figure 32**, the energy cost can be the predominant parameter affecting the market scale of the technology.

According to the identified parameters, the analysis tried to qualitatively assess the overall potentiality of SAHPs technology, as represented in **Figure 33**. Generally, the most suitable countries resulted the ones characterized by high irradiation availability, high H&C demand, and high energy cost. Such a deep analysis highlighted also that it is not possible to identify the potentiality of this technology only based on renewable resources availability. This is also confirmed by the fact that other solar-assisted technologies, like photovoltaic, achieved their

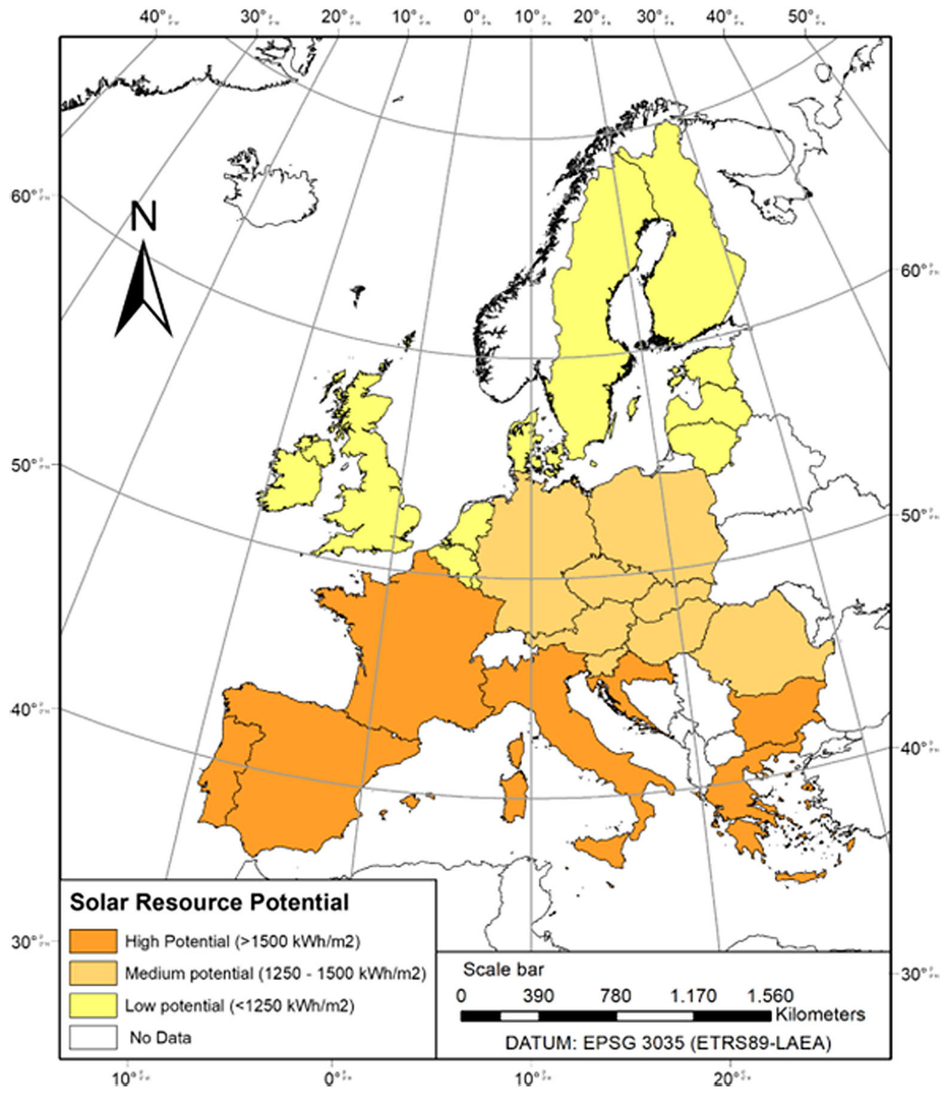


Figure 28. Classification according to solar resource potential. Reproduced with permission.[135] Copyright 2018, SunHorizon project.

highest share in countries with low-to-medium solar irradiation availability. This was possible thanks to other drivers that supported the innovative technology application.

The above-described approach is an example of the need to carefully consider both technical and nontechnical aspects in the investigation of the potentiality of nonstandard technologies. The approach can be further improved and refined, for instance, adding details about the different technologies' integration, the specific H&C demand, etc., but it can be considered as a good basis for a preliminary screening that is applicable to different geographical areas and market/regulatory scenarios.

5. Market Aspects

As presented in Section 4, the market for sun-coupled heat pumps worldwide is strongly dependent on several drivers, such as the policy framework, the cost of energy, and the market acceptance, i.e., the perception of the various stakeholders which motivates them to implement the technology in buildings. The situation in the different parts of the world is extremely complex and in the present section only the predominant markets, for which available data in the open literature were found, are considered.

5.1. European Union

The European Union is one of the main markets worldwide, with more than 16 million heat pumps installed.[138] One of the reasons for such an outbreak is the policy framework, with a strong push of the EU toward a decarbonization of the heating and cooling sector by 2030. According to the data from European Heat Pumps Association (EHPA), from 2009 till 2018, the market for heat pumps has grown from about 800 thousand units sold till 1.3 million units sold annually. It is interesting to notice, as shown in **Figure 34**, that air source heat pumps are vastly

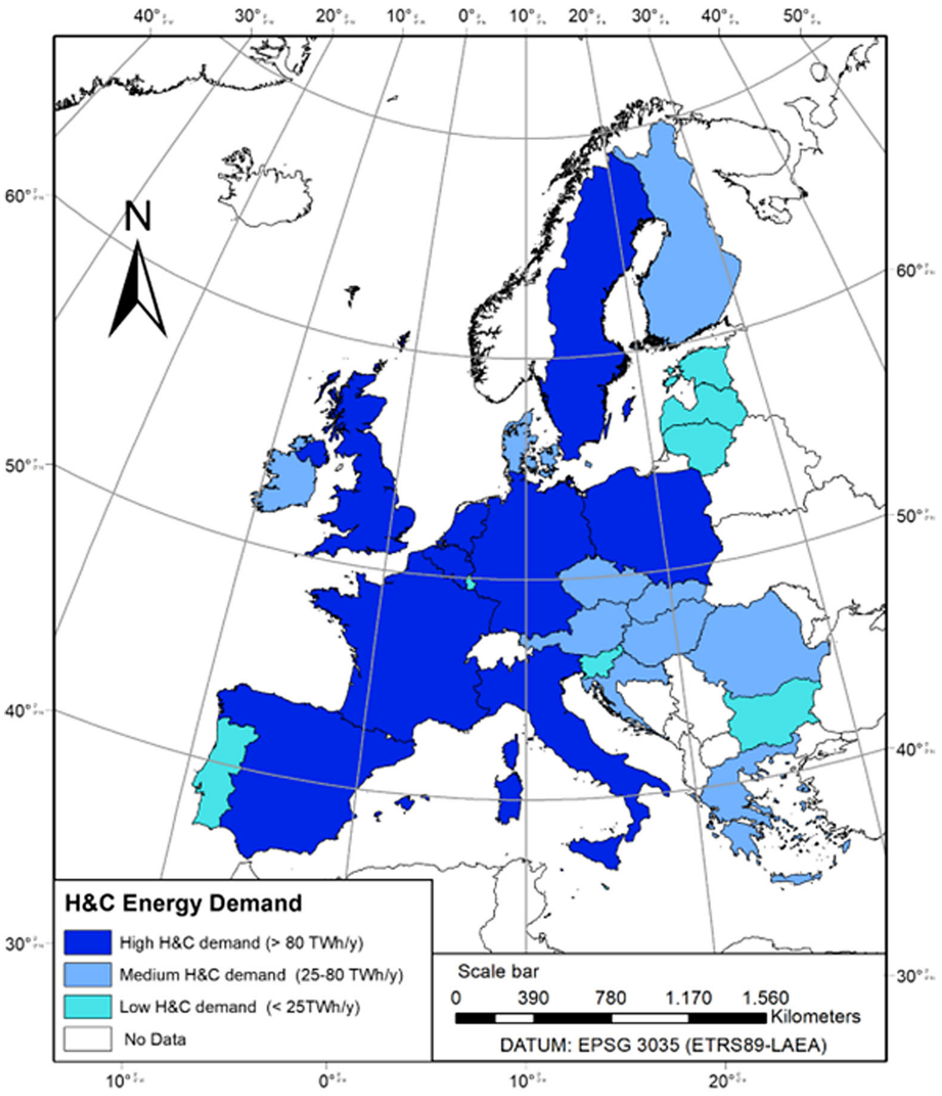


Figure 29. Classification according to total final demand for H&C. Reproduced with permission.[135] Copyright 2018, SunHorizon project.

dominating the market, with solar-assisted HPs (which go under the "reversible other" and "hybrid" categories) account for less than 25% of the current market, thus indicating the need for dedicated policies, subsidies, and dedicated campaigns. As indicated in the study by Kegel et al.,[139] the market for solar systems which include solar thermal collectors and heat pumps is mainly dominated by Germany and Finland, with the most relevant application as large centralized systems within solar districts, rather than in residential applications. In case of residential/commercial applications, one solution that is currently gaining market interest is the combination of PV/T systems with heat pumps for H&C, especially in countries where public incentives are present, such as France, Denmark, and Germany.[139] In the industrial sector, solar-assisted HPs still represent a niche market but still showing a linear growth from some years.[140]

The evident outcome of this analysis is that the Southern Europe regions, indicated in Section 4.2 as the most suitable areas for the application of solar-assisted HPs, still need to increase the penetration of such technology. The attention of economic stakeholders shall be focused on these markets; it is then necessary to support them to improve the knowledge and analysis of sun-coupled technologies in order to offer a proposal for a market that just collects a complex and wide range of products and solutions.

5.2. North America

In the USA, the market for solar heat pumps is mainly dominated by absorption heaters. In 2018, 4.5 million units in the 4.8–11.3 kW range, i.e., for residential heating, were sold. The main driver for such solar heat pump market performance lies in the financial incentives, with subsidies on loans and taxes reduction, as well as the Energy Standards for Public Buildings and Energy Efficiency Resource Standard. In Canada, the push toward heat pump adoption is led by the Market Transformation Roadmap on decarbonization of the

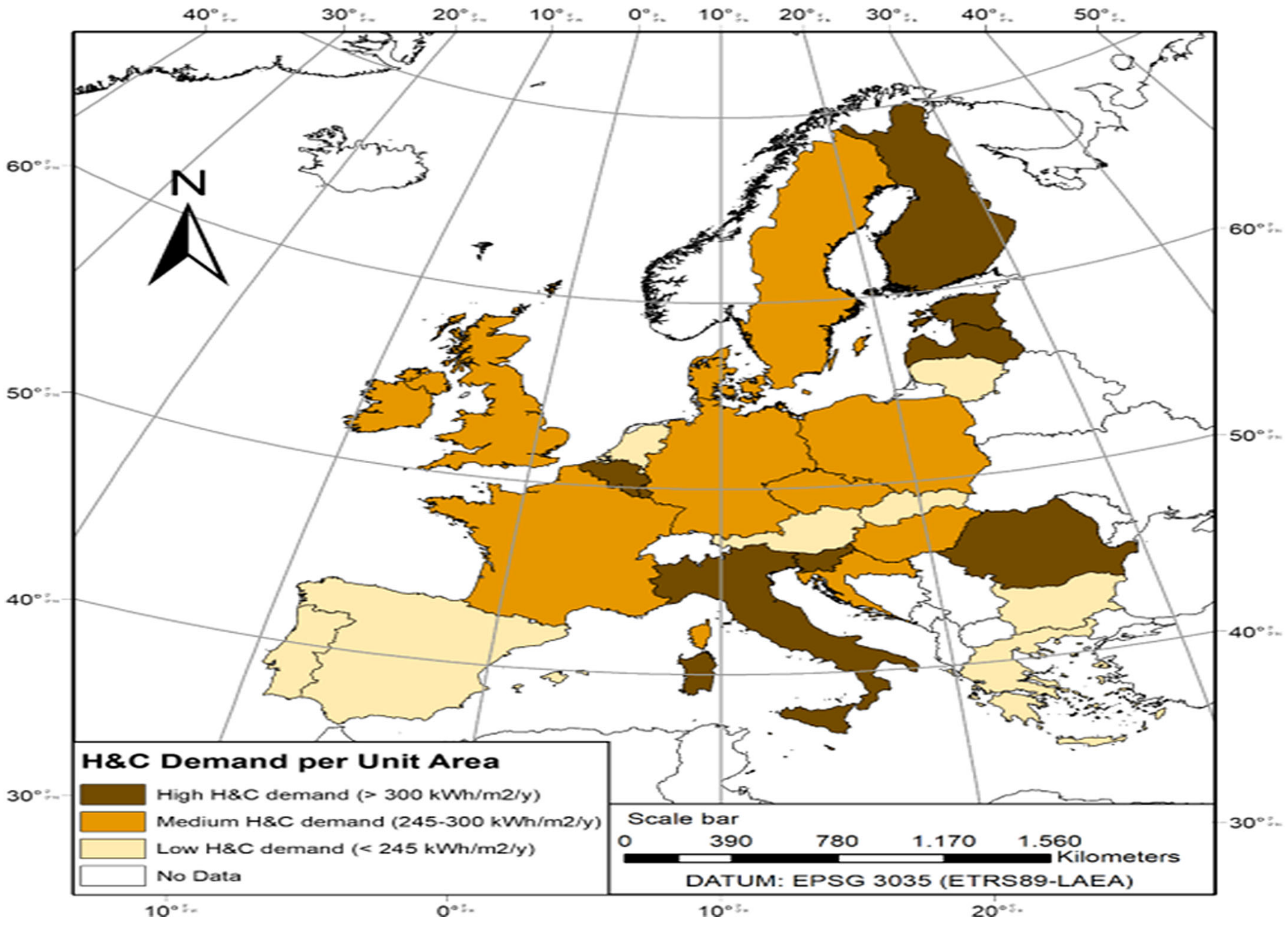


Figure 30. Classification according to H&C demand per unit area. Reproduced with permission.[135] Copyright 2018, SunHorizon project.

built environment. The main challenges faced regarding the adoption of heat pumps in Canada are the strong regional variations in both climate and utility rates, as well as electric grid implications of greater heat pump adoption. Moreover, the climatic conditions of Canada cause a low seasonal efficiency of the heat pumps compared to other heating systems, which limits the trust from customers. Accordingly, a solution identified is the definition of a new standard that takes into account such issues.[139]

5.3. East Asia

The main market for heat pumps in East Asia is China. In China, the main driver for the shift toward heat pumps is the comprehensive set of laws and regulations for the reduction in peak carbon emissions by 65% by 2030 (on 2015 reference basis).[141] Use of renewable energy and clean heating are among the China's policy priorities identified and in the "work program on air pollution prevention and control in Beijing, Tianjin, Hebei, and surrounding areas in 2017," it is stated that heat pumps should be the main heating system for new residential buildings. However, the market is mainly dominated by air source heat pumps used as stand-alone units. The use of solar heat pumps is more common in rural regions, where the connection to the electric grid is less stable.[142] The main barrier to the wide deployment of sun-coupled heat pump technology in China is the cost of the overall system, compared to the cost of the heat pump alone.[141]

5.4. Market Drivers and Challenges

From what reported in Section 4 and according to ref. [143], the expansion of sun-coupled heat pumps is possible only when different conditions are met. Economic factors are the main limiting barrier because a combined solar heat pump system has a high capital cost, which pays back only if a significant increase in the efficiency of energy generation is achieved or if suitable incentives are put in force. In addition, as already reported in the exemplary analysis of Section 4.2, the cheaper price of gas and oil compared to electricity is one of the biggest challenges to be overcome for the wide market spread of the investigated technology. From a technical point of view, the identified targets are the development of digitalization and integration with Internet of Things (IoT) and the harmonization of the definition of the heat pump performance, giving the currently diverse testing procedures and definitions among different countries. It is then evident that the HP market growth is strongly linked to a

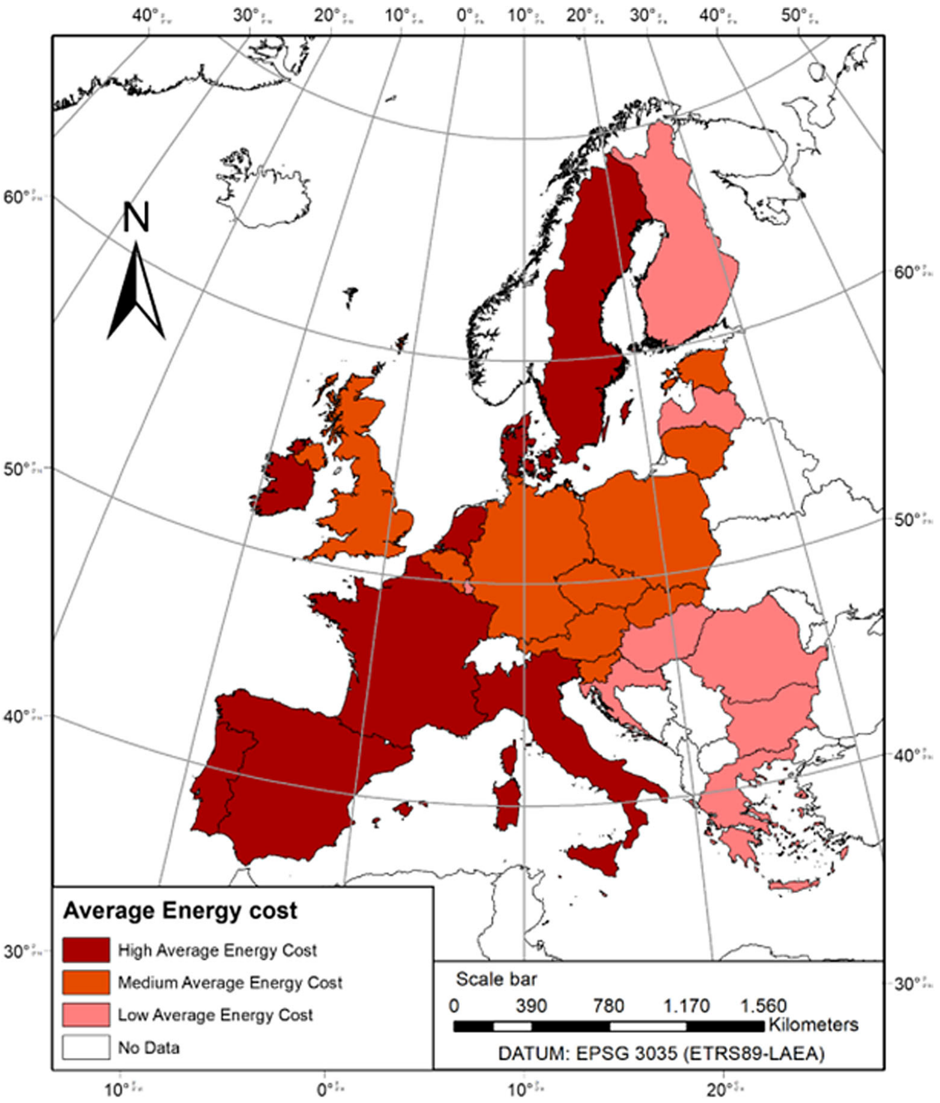


Figure 31. Classification according to average energy cost. Reproduced with permission.[135] Copyright 2018, SunHorizon project.

policy framework that requires high-efficiency systems for new and renovated buildings, providing also financial subsidies and governmental supports to heat pumps especially for the commercial and industrial sectors.

6. Social Aspects

Apart from technical and market issues, a crucial point in the wide deployment of heat pump technologies is represented by the social perception of the technology. This is especially true for systems in which more components are combined together, as is the case of the HPs coupled to the solar collectors. Indeed, in some countries, such as South Korea,[144] the social barriers are among the most relevant ones for the acceptance of the technology, whereas in Finland there is a strong social push toward heat pump technology in combination with solar components,[145] thus indicating that they cannot be neglected in the overall evaluation of the potential for the technology. With the European project SunHorizon, social acceptance for SAHPs was analyzed through a comprehensive evaluation of the literature data, review of project reports, and a dedicated survey. Detailed results are reported in ref. [143] for the European market. Within the ENTRANZE project,[146] the macro- and micro-level aspects influencing the adoption of renewable based technologies were evaluated and the relevant stakeholders at different levels were identified, as shown in **Figure 35**.

Similarly, the stakeholders identified in ref. [143] include private building owner, equipment manufacturers, installers, public building owner, energy utilities, residents, ESCOs, real estate developers, and energy consultants. The results from the literature analysis indicate that the main drivers are the availability of information about technology, financial aspects, and sociodemographic factors. Interestingly, the environmental aspect is a very influential factor for fostering adoption only in European studies. Surveys on market and social acceptance

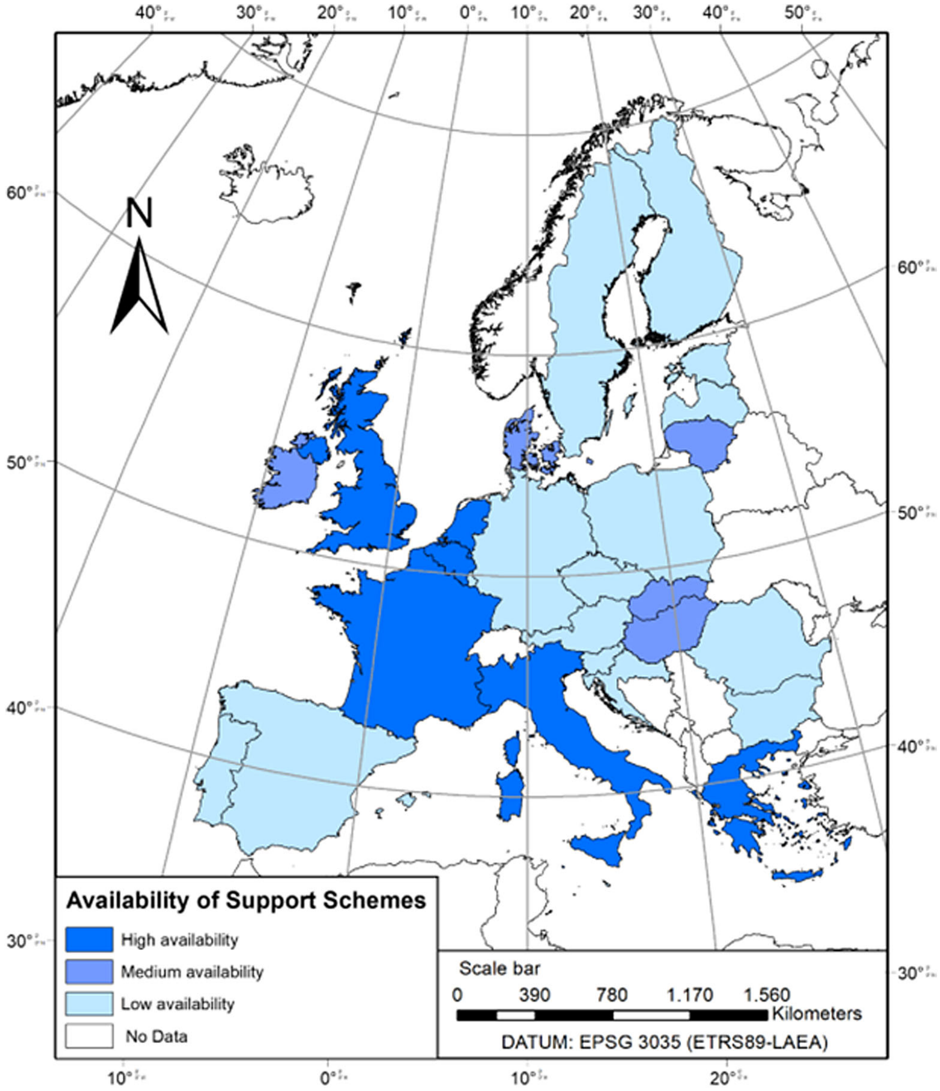


Figure 32. Classification according to availability of support schemes. Reproduced with permission.[135] Copyright 2018, SunHorizon project.

barriers were also made within several projects, mainly focused on residents' level of satisfaction. In general, the main barrier blocking or slowing the adoption of heat pumps, especially when more than one component is present, which is the case of solar-assisted systems, is the lack of information on the technology. Other factors negatively affecting the initial satisfaction toward the solutions proposed were the concern on the installers and the annoyances during the renovation process. However, when the surveys were made in two stages, the satisfaction toward the new solution increased once people started to be familiar and in all the cases when they were implemented in buildings. Aesthetic, reduction in energy consumption and economic savings were all considered positive factors that increased the implementation of heat pumps positive for their living conditions. The survey reported in ref. [143] instead includes also different stakeholders categories (businesspersons, public building owners, private building owners, and the public). For all categories, the economic aspects are perceived as the main barriers, especially among public building owners and the public. Businesspersons are the most skeptical toward the new technologies, indicating as barriers the lack of information, trust, inadequateness of business models, and legal barriers. Private building owners are the stakeholder groups showing the most positive attitude toward SAHPs. It is interesting to notice that only the private building owners expressed concern toward solar irradiation, which is, however, mostly seen as a motivator toward the adoption in the EU countries for the technology. A common aspect for all countries is that SAHPs are considered a clean technology that reduces pollution to a very large extent.

According to such an overview, the most important measure to foster the adoption of the investigated technology is the realization of informative campaigns to raise awareness among citizens and all relevant stakeholders on this topic. In particular, information on the environmental and landscape-related benefits should be given. Installers are an important stakeholder group to be targeted because successful installation and trust from residents are strongly linked to their level of preparation and confidence with the technology.

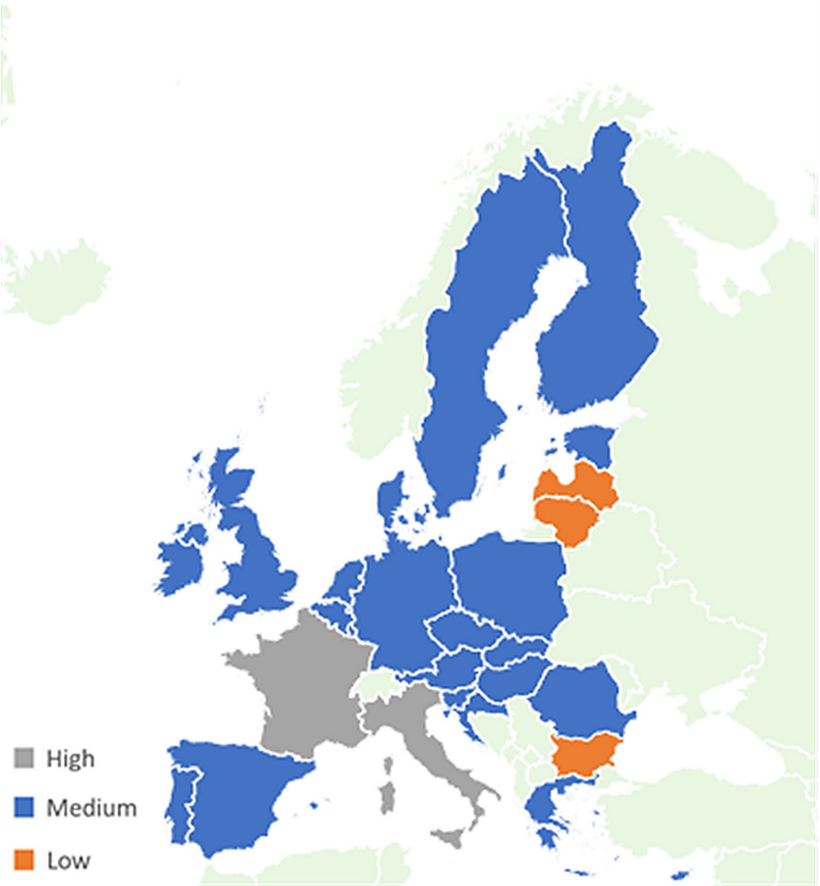


Figure 33. Classification according to the overall suitability of solar-assisted technologies installation.

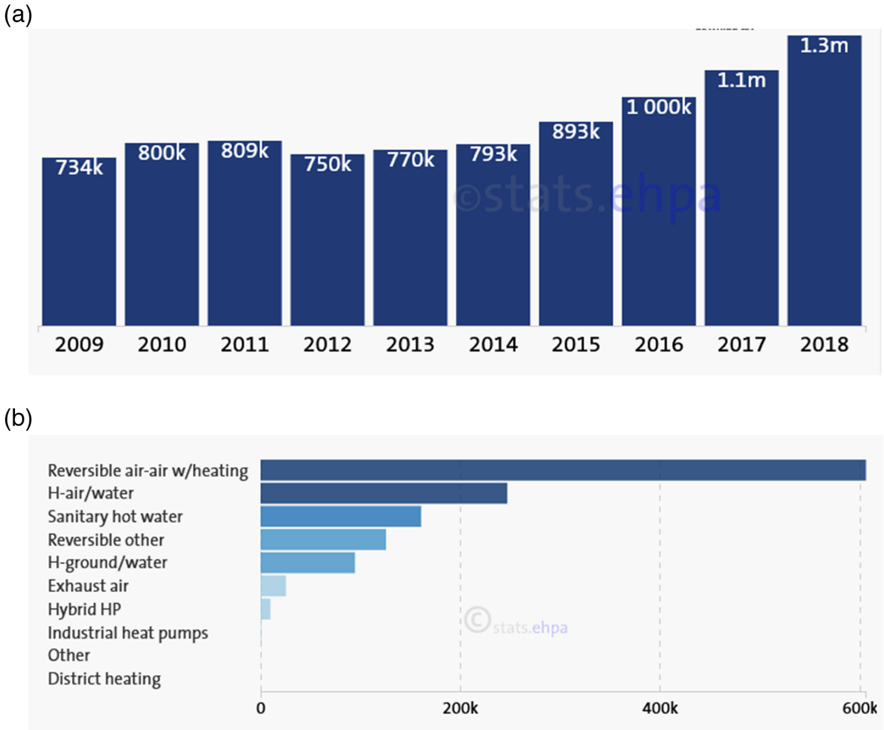


Figure 34. a) Number of heat pumps sold in the EU and b) their distribution according to the source type. H- indicates primary heating function. Reproduced with permission.[138] 2022, EHPA.

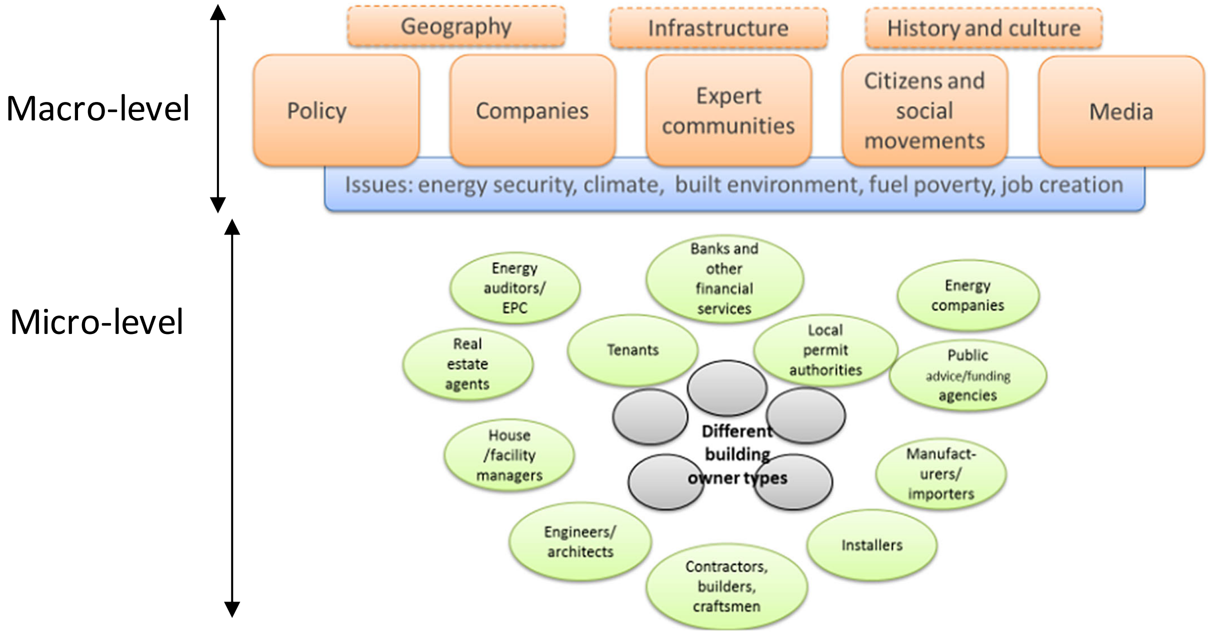


Figure 35. Macro- and micro-level factors influencing acceptance and adoption of nearly zero energy and renewable heating and cooling solutions. Adapted with permission.[146] Copyright 2022, Elsevier.

More efforts shall be devoted to the research on architecture integration between solar-assisted HPs and historical and cultural heritage buildings that are widespread in almost all European centers, from bigger cities to the small towns.

7. Conclusions and Identification of Future Trends/Recommendations

Within the present article, an overview of the literature and market/project studies was carried out to evaluate the feasibility of SAHP in increasing the share of renewables in the heating and cooling sector, by exploiting in a synergic way the main features of two renewable and low-carbon technologies. The promising potential of the heat pumps was addressed as follows: 1) At technical level, by evaluating the application of heat pumps in different climatic conditions. To this aim, the different technological options and layouts for the HPs considering the state-of-art were presented, suggesting the main areas of applications, advantages, and drawbacks. In addition, a methodology that allows the qualitative estimation of the potential for sun-coupled heat pump technology in different climates and countries was presented, which can be used as a preliminary screening basis. 2) At market level, by defining the main market drivers worldwide and identifying the way to overcome market barriers. Growing market trends are registered worldwide, especially boosted by energy efficiency measures in residential applications, whereas investments for commercial and industrial cases are still limited. Future research trends to improve market penetration are the development of digitalization and integration with IoT and the harmonization of the definition of the heat pump performances, giving the currently diverse testing procedures and definitions among different countries. At policy/producers' level, there is need for governmental supports to heat pumps for the commercial and industrial sectors, the reduction of the capital cost for the heat pump and the cheaper price of gas and oil compared to electricity. 3) At social level, a good perception of the technology was generally evidenced but the need for informative campaigns and specific formation of installers are key issues to ensure a high level of satisfaction of the different stakeholders. Accordingly, several efforts are needed in the next future for awareness raising to create curiosity and generate knowledge on the technology among technical people (installers, ESCOs, energy utilities) and the wide public, which represents in the end the audience of residents and end-users of the technology.

Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement no. 818329 (SunHorizon).

Open Access Funding provided by Consiglio Nazionale delle Ricerche within the CRUI-CARE Agreement.

Conflict of Interest

The authors declare no conflict of interest.

Keywords

heat pumps, solar energy, heating, cooling, renewables, drying, water treatment

Received: January 13, 2022
Revised: May 5, 2022
Published online: May 26, 2022

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