Renewable and Sustainable Energy Reviews 226 (2026) 116197

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Comprehensive review on heat pump systems integrated with phase change material-based thermal energy storage for sustainable building heating

C. Suresh [a,b], Abhishek Awasthi [a], Binit Kumar [a], Hyoungsoon Lee [b,*], Yongseok Jeon [a,**]

[a] Department of Mechanical Engineering, Ajou University, Suwon, 16499, Republic of Korea
[b] School of Mechanical Engineering, Chung-Ang University, Seoul, 06974, Republic of Korea

ARTICLE INFO

Keywords:
Heat pump
Phase change material
Thermal energy storage
Energy savings
Environment
Sustainable building heating

ABSTRACT

Heat pumps (HPs) are promising solutions for sustainable building heating owing to their high efficiency and low carbon footprint. However, their performance is often limited by challenges such as defrosting, peak electricity demand, and reliance on intermittent renewable sources. Integrating phase change material (PCM)-based thermal energy storage (TES) with HP systems has emerged as an effective strategy for overcoming these barriers. This review presents a comprehensive analysis of PCM-TES integration with various HP technologies, including air-source, ground-source, dual-source, and solar-assisted systems. PCM-based TES enables thermal load shifting, enhances operational stability, and shortens the defrosting duration by up to 75 %. This paper discusses the optimal PCM selection criteria, TES configurations on both the evaporator and condenser sides, and TES performance enhancement methods. Among the reviewed technologies, dual-source and photovoltaic thermal-assisted HPs with PCM-TES demonstrated the most potential in terms of energy efficiency and emission reduction. Comparative evaluations highlighted improved system COP, reduced peak energy consumption, and enhanced year-round performance. This review provides valuable insights for the development of next-generation HP systems and offers guidance for researchers, designers, and policymakers aiming to promote low-carbon energy-resilient building technologies.

1. Introduction

The pursuit of thermal comfort in buildings has become increasingly significant owing to the global rise in living standards and escalating impacts of climate change. As the population demands higher indoor environmental quality, especially in regions with extreme climates, energy consumption for space heating and cooling has surged. To meet this demand, fossil fuels have been extensively exploited, which has resulted in substantial greenhouse gas emissions and accelerated environmental degradation [1]. According to recent global energy statistics, the building sector accounts for approximately 40 % of the world's total energy consumption [2], with residential space heating and cooling accounting for nearly 61 % of this energy use [3]. These trends underscore the urgent need to decarbonize building energy systems and enhance energy efficiency as part of the global strategies to mitigate climate change [4].

Hence, heat pump (HP) technology has gained attention as a sustainable alternative to conventional heating systems such as gas-fired boilers and electric resistance heaters, which are typically powered by fossil fuels [5]. A heat pump is an energy-efficient device that transfers heat from a low-temperature source to a high-temperature sink using minimal electrical energy input [6]. Unlike traditional combustion-based systems, HPs do not directly burn fuel to generate heat and their operation results in significantly lower carbon emissions, positioning them as a crucial technology for achieving carbon-neutral goals in the building sector.

HPs can be broadly classified into two categories based on their driving energy sources: electrically and thermally driven heat pumps [7]. Electrically driven HPs utilize electricity to operate a compressor, enabling efficient heat transfer via vapor-compression cycles. These systems have been widely adopted in both residential and commercial settings owing to their compact design, operational reliability, and relatively simple maintenance requirements [8]. In the aspect of energy efficiency and carbon emissions, electrically driven HPs offer superior energy efficiency and lower carbon footprints as compared with electric-resistant heating and other boiler conventional heating methods as given in Table 1. In contrast to traditional heating systems like electric

* Corresponding author.
** Corresponding author.
E-mail addresses: leeh@cau.ac.kr (H. Lee), ysjeon@ajou.ac.kr (Y. Jeon).

https://doi.org/10.1016/j.rser.2025.116197
Received 16 April 2025; Received in revised form 12 July 2025; Accepted 10 August 2025
Available online 21 August 2025

Abbreviations

ASHP	Air source heat pump
COP	Co-efficient of performance
DCS	Data centers
GHEs	Ground heat exchangers
GSHP	Ground source heat pump
HP	Heat pump
HTF	Heat transfer fluid
LCC	Life cycle cost
LTES	Latent thermal energy storage
NGSH	Natural gas heating
PCM	Phase change material
PEC	Primary energy consumption
PVT	Photovoltaic thermal
SA	Solar assisted
SSHP	Sewage source heat pump
SAHP	Solar assisted heat pump
TES	Thermal energy storage
WSHP	Water source heat pump
WHSHP	Waste heat source heat pump

Table 1
Comparison of different heating systems with energy efficiency and carbon emissions [9,10].

No	Heating systems	Energy efficiency	Co_2 emissions (kg Co_2/kwh)
1	Electric heating	0.36	0.40
2	Coal fired boiler	0.70	0.49
3	Gas-oil fired boiler	0.80	0.35
4	LPG fired boiler	0.80	0.31
5	Natural gas boiler	0.80	0.24
6	Electric driven HP	2.50	0.19

heating (36 % energy efficiency, 0.4 kg CO_2/kWh carbon emission) and gas fired boilers (80 % energy efficiency, 0.24 kg CO_2/kWh carbon emission), electrically driven HP achieved significantly higher energy efficiency (up to 250 %) and lower carbon emissions (0.19 kg CO_2/kWh), respectively [9,10].

However, their heavy reliance on electricity poses a challenge to power grid stability, particularly during peak demand periods in the cold seasons [11]. Heat pumps that run on electricity generated by renewable energy sources reduce emissions more significantly than those that run on electricity generated by conventional fuels.

1.1. Heat pump (HP) working

An electric compression HP is a device that employs a refrigeration cycle to transfer heat from one source to another. Heat generally moves from higher to lower temperatures, but an HP functions as a “pump" to transport the heat in the reverse direction. Therefore, an HP can be utilized for both air conditioning in the summer and space heating in the winter [12]. The HP components include: an evaporator, a condenser, a compressor, and an expansion valve. A refrigerant, often referred to as the “working fluid," receives heat from heat sources (ambient air) through the evaporator turned into a vapor form and this vapor refrigerant is compressed in a compressor to a high temperature and pressure. Subsequently, a high-pressure, high-temperature refrigerant enters the condenser to deliver heat to the building space heat applications. Finally, the refrigerant returned to its original state by passing or expanding through the expansion valve [13]. Similarly, when the operation of the heat pump is altered for cooling in summer, the indoor coil acts as an evaporator that absorbs heat from the space to be cooled, and this heat is then discharged to the outside via the condenser [14]. An HP generally operates under a vapor compressor cycle, and its performance is determined by the quantity of heat energy delivered to the amount of energy consumed as an input. The COP was used to quantify the HP performance and was determined using Eq. (1) [15], which is the ratio of the energy output Q (heating or cooling output) to the electric energy input W consumed by the compressor and auxiliary pumps.

$$COP = \frac{Q}{W} \tag{1}$$

Furthermore, HPs are classified based on their thermal sources: air source heat pipes (ASHP), water source heat pumps (WSHP), solar-assisted heat pumps (SAHP), waste heat source heat pumps (WHSHP), and ground source heat pumps (GSHP) [16], as shown in Fig. 1. Based on the temperature range, the HPs are categorized into low (<60 °C), medium (60–100 °C) and high temperature HPs (>200 °C) [17]. Currently, low- and medium-temperature HPs are the most widely employed and mature technologies on the market. High-temperature HPs are in the development phase, and their development will ensure the utilization of high-grade thermal energy in industrial applications [18].

Other than the vapor compression HP, there is a thermally driven HP such as sorption HP which utilizes thermal energy, often sourced from renewable sources or waste heat for the operation. Sorption technology is categorized into absorption and adsorption, which can be used in thermal driven HPs. Absorption HP also comprises of four components like the vapor compressor HP and only the electrical driven compressor is replaced with the thermal compressor. The absorber and generator together referred to as a thermal compressor. The evaporator absorbs low grade heat from thermal sources turned into a form as a vapor refrigerant (ammonia) and then supplied to the absorber. In the absorber, vapor refrigerant is mixed with absorbent solution (lithium bromide) to form as a rich solution and this solution is pumped to the generator through the pump. The generator receives heat from solar thermal or waste heat to generate high temperature refrigerant vapor as well as to separate from the bromide solution which has a higher boiling point. This high temperature vapor flows to condenser for transferring the heat to the building applications and then the condensed refrigerant flows through the expansion valve to drop the temperature as well as pressure and move to the evaporator. Further, the weak solution bromide is returned to the absorber for absorbing the ammonia refrigerant coming from the evaporator and this cycle repeats [19]. The adsorption HP working principle is also similar to the absorption HP and the only difference is the absorbent materials. The solid adsorbent material (activated carbon or silica gel) in the absorber bed is used for absorbing and desorbing the refrigerant, instead of generator and absorber in absorption HP, which has a liquid absorbent material [20].

While these systems have the advantages of reduced electricity dependence and lower environmental impact, they typically exhibit lower coefficients of performance (COP) and require a larger physical space owing to their design complexity [21]. Nonetheless, thermally driven HPs are receiving renewed interest, particularly in off-grid or renewable-integrated systems, where their independence from electrical infrastructure has become advantageous [22]. According to the research studies, HP has emerged as a promising alternative to conventional building heating systems because of its higher energy efficiency and less carbon impact. However, despite their advantages, the conventional HPs persists certain challenges that include frost formation, seasonal performance fluctuation, energy supply-demand imbalance, and intermittency of renewable sources. These challenges restrict the potential of widespread in large-scale systems, resilient and cost-effective heating decarbonization. The operational stability and economic feasibility of all HP systems are also impacted by dynamic loads, shifting occupancy trends, and varying electricity pricing. In order to solve these problems, researchers developed a thermal energy storage (TES) technology that may be used in conjunction with HP to minimize or eliminate those problems.

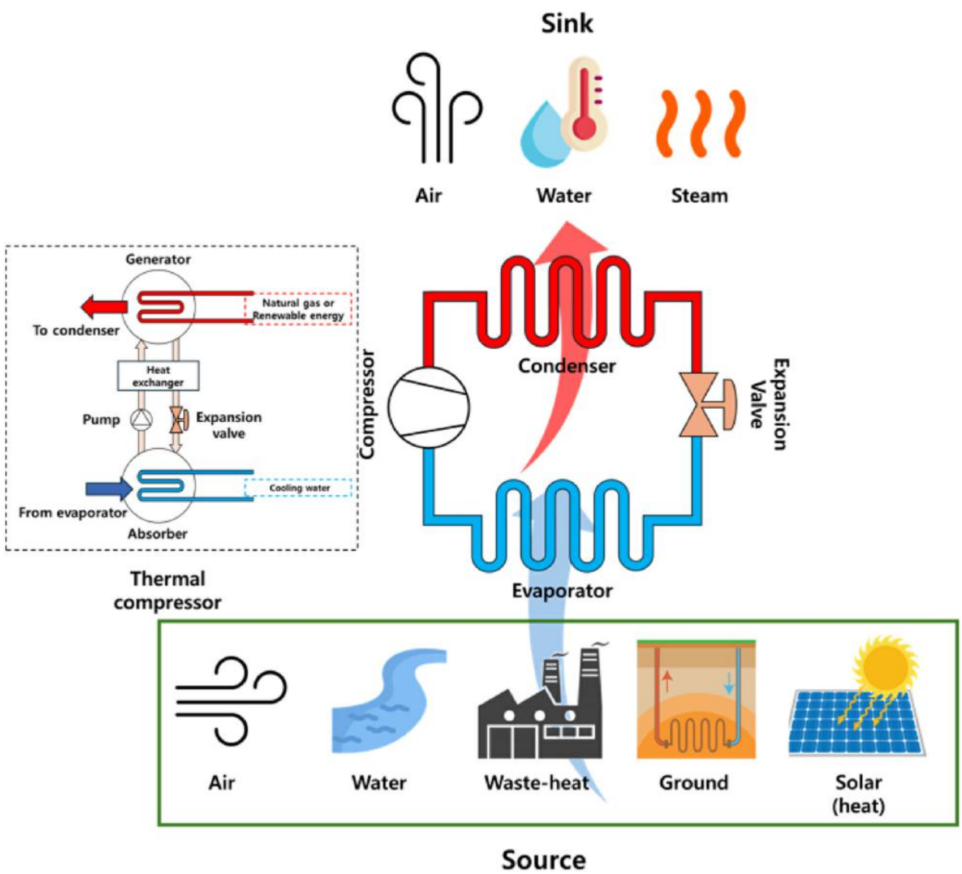

Fig. 1. Classification of heat pumps based on driven energy and thermal source.

This study explored the integration of phase change material (PCM)-based thermal energy storage (TES) with various heat pump configurations. While previous research has primarily focused on individual HP types (e.g., air-source or solar-assisted) and limited placement strategies. Existing reviews in this field have often concentrated on HP integration with TES systems and their performance metrices, however they have not provided significant insights into PCM-based TES systems or the related emerging technologies and their real-time issues for performance enhancement. Most of the existing reviews have not cover holistic energy, economic, and environmental perspectives, which is an important factor for commercialization and sustainability. Thus, this study aims to expand beyond a conventional descriptive study of literature by methodically examining various HP systems that are integrated with PCM-TES, comparing and contrasting their advantages and disadvantages, finding gaps, and projecting possible future directions.

Generally. commercial HP requires electric energy as an input to operate the system, and this energy supply and demand will always be imbalanced according to time and season [23]. Large-scale heat pump installations may increase dependency on fossil-fuel power plants by causing electrical networks under a lot of stress, particularly during concurrent cold-weather peak times. By combining TES systems with HPs have a significant potential to decouple energy generation from thermal demand, that allows demand side control, peak shaving and flexibility in operation. Therefore, TES and demand response [24] may be implemented to reduce the peak electricity demand [25] and the utilization of less expensive non-peak electricity leads to a reduction in grid power loss and economic costs., Furthermore, the energy for HP may be derived from electricity generated through renewable energy sources, which is intermittent in nature and varies with time [26]. Moreover, to reduce the peak load demand on the grid and ensure a constant supply of heat from renewable energy sources, integration or coupling of the TES system to the heat pump will be a viable solution [27].

The TES can stock energy during a nonpeak load or sunny day, and the stored energy can be retrieved during the peak load period or on a non-sunny day [28]. Furthermore, the integration of TES demonstrates load shifts and may improve the heat output to meet the thermal demand without the need for additional HPs [29].

TES is an energy-conservation technology that includes sensible heat storage, latent heat storage, and thermochemical storage [30]. Sensible storage reserves the thermal energy by raising the temperature of storage material without undergoing any phase change during the energy supply and recovery processes. Sensible storage is the most mature and simple technology, but the applications are limited due to the minimal energy storage density and rapid temperature decrement [31]. Thermo-chemical storage reserves the thermal energy through reversible chemical reactions and undergoes chemical reactions during charging and discharging of energy. This storage system is in its initial stage and significant research is required for real time applications [32]. The latent storage system accumulates the thermal energy in the storage material by changing the phase of the material during both the energy supply and recovery processes. Therefore, materials used to store energy in these systems are known as phase change materials (PCM). Latent heat storage has received significant attention and has great potential in various applications, such as heat pumps [33], electronic cooling [34], thermal management of batteries [35], and building cooling [36]. PCMs utilized in latent TES exhibit a higher energy storage density and lower temperature swings during the heat storage or release process compared with sensible storage [37]. These benefits make PCM a possible choice for combing with HPs that can meet thermal demands and operate at constant-temperature conditions.

To limit the review, only vapor-compression HPs are considered as the main focus area of this study, because of their substantial adaptation rate, commercial development, and predominant share in building applications for heating. Therefore, the scope of the present study is limited to various vapor compression HPs coupled with PCM based TES for building heating applications. Even though sorption HP is outside the current scope of review, a thorough analysis of PCM-TES integration with thermally powered or sorption HP is noted as an important focused area for future study. To explore the significance of vapor compression HP-coupled PCM-based TES, a comprehensive bibliographic assessment of the advancements in this field of research was conducted. The Scopus database was used for executing the search analysis with keywords as "heat pumps, heat pumps with thermal energy storage and heat pumps with PCM or latent thermal storage." The abstracts, keywords, and titles of publications were considered in the search analysis to identify relevant articles. Based on the analysis, 49361 articles for HPs, 3982 for HP with TES, and 573 for HP with PCM or LTES, as shown in Fig. 2 (a). Furthermore, Fig. 2 (b) depicts the percentage share, which was observed to be 92 %, 7 %, and 1 % for HPs, HP-TES, HP-PCM, and LTES, respectively. From 2015, there has been a significant growth in HP-TES, and a gradual increase was observed in HP-PCM or LTES as shown in Fig. 2 (a).

From these, it was reported that significant research has been conducted on HP-TES and proved that HP-coupled TES systems are a promising approach for the sustainable heating of buildings with enhanced performance, consistent heat sources from renewable energy, and energy savings with reduced carbon emissions. Based on the percentage share of articles, there is a lack of significant research on HP coupled with PCM-based TES systems.

The main objective of this study is to provide a systematic overview of various thermal-source HPs, with a special emphasis on their integration into PCM-based TES systems. The paper is structured as follows by covering detailed aspects: a) operational mechanism of HP and their classifications based on various thermal sources, b) problems of conventional HP and significance of HP coupled to PCM-based TES associated with PCM selection criteria, c) integration of PCM on HP evaporators and condensers with their benefits, d) coupling of PCM-based TES to various thermal source HPs with potential benefits and challenges as well as emerging performance-enhanced TES technologies for HPs, e) emerging PCM based TES technologies to enhance performance energy, f) energy, economic, and environmental analysis for clear understating of the systems and commercialization, and g) conclusions with future directions. This study provides valuable insights for scientists, researchers, and policymakers for a roadmap of future advancements, clear understanding, and innovative technology for the commercialization of sustainable HP systems for building heating applications.

2. PCMs for heat pumps (HPs)

PCM s exhibits greater energy storage density and latent heat, that enables more compact TES devices. These characteristics allow for HP integration, which stabilizes source or sink temperatures and shifts demand load. PCMs are classified into the solid–solid, solid–liquid, and liquid phases according to their phase transition. Among these, solid–liquid PCMs are widely employed and are practically reliable because of the lower change in volume during the phase change and constant temperature with higher energy storage [39]. Fig. 3 shows the typical solid–liquid phase change during heat storage or the release phenomenon of the PCM [40]. However, solid–solid PCM have lower energy storage, and liquid-gas PCM require large containers owing to the greater change in volume during the phase transition [41]. Therefore, solid–liquid PCM are primarily considered for all thermal applications [42].

According to their chemical compositions, PCMs are generally categorized into three types: organic, inorganic, and eutectic, as shown in Fig. 4 (a). Organic PCMs are chemically and thermally stable, possess a high storage capacity, and are readily available on the market [43]. Owing to these advantages, paraffin-embedded organic PCM have drawn significant interest and are widely used in thermal applications. However, organic PCMs exhibit poor thermal conductivities, generally ranging from 0.1 to 0.35 w/mK [44]. Thermal conductivity is the main property that reflects heat transfer, and poor thermal conductivity leads to reduced heat transfer, a lower thermal storage rate, and a lower COP of HPs. To overcome this drawback, numerous researchers have implemented various approaches, including composite PCMs, encapsulations, metal foams, fins, and nanoparticles [45–48]. The introduction of metal foams, fins, and cascade PCMs has received increasing attention owing to their greater heat transfer enhancement [49,50].

Furthermore, inorganic PCMs, including salt hydrates, chlorides, and metallics, are primarily utilized for medium-temperature applications. Inorganic PCMs exhibit better thermal conductivity, specific heat, thermal stability, nontoxicity, and low costs. However, there are issues associated with corrosion, phase segregation, and supercooling [51]. The addition of thickening or nucleating chemicals to inorganic PCM is a standard solution to the supercooling and phase separation issues. Appropriate encapsulation techniques such as microencapsulation,

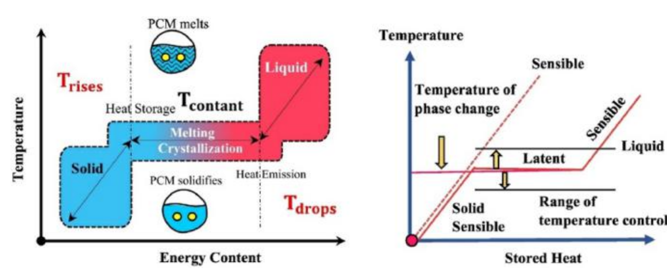

Fig. 3. Phase change phenomenon of PCM heat storage and release [40].

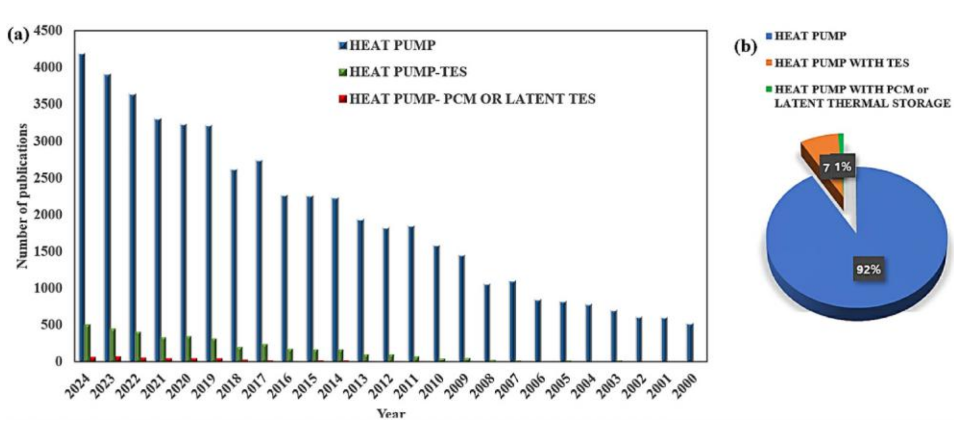

Fig. 2. Research publications a) trend of HP technology (2000–2024) b) Percentage share [38].

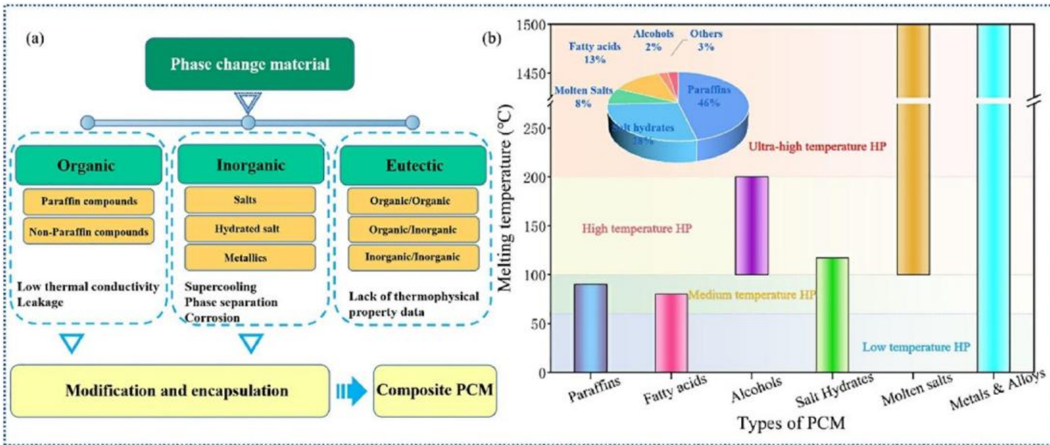

Fig. 4. a) Classification of Solid-liquid PCMs b) Application of various PCMs to HPs [59].

shape stabilization, and ceramic materials can address the issue of container corrosion [52]. Eutectic PCMs are a mixture of two PCMs like organic–inorganic and inorganic-inorganic PCMs. Eutectic PCMs are not practically mature, and there is a lack of a property database for these PCMs [53]. Although there are many different types of PCM in the market, it is crucial to choose the best PCM for a particular application. Therefore, PCMs should be carefully selected, depending primarily on the operational temperature of the HP, end-user applications, and chemical characteristics. According to research study, a PCM should have a melting temperature of 45 °C as the condenser temperature range between 50 and 40 °C [54]. The phase transition temperature of a PCM should be configured between 45 and 50 °C as maximum HP outlet temperature corresponds to 55 °C and consumers demand hot water at 45 °C [55]. This indicates that the optimal phase transitional temperature of the PCM can be lower than the maximum condensing temperature of the HP and equal to or greater than the HTF temperature for end use. Thus, identifying the appropriate PCM phase change temperature is crucial to maximize the TES storage unit utilization.

The selection criteria for the PCMs from various aspects of the HPs are shown in Fig. 5 [56,57]. Fig. 4 (b) summarizes the PCMs phase change temperatures that can be utilized in HP under different operating temperatures as well as the share of various PCM categories that exist in the literature. Even though phase change temperature is unquestionably a critical component in ensuring compliance with the thermal applications, the concept of “optimal" selection inherently considers a wide spectrum of characteristics. In addition to practical considerations like price, availability, and environmental impact, these include PCM thermo-physical properties like thermal conductivity (which influences heat transfer rates), chemical stability, compatibility of encapsulating materials, cycle durability, and latent heat capacity (which establishes the energy storage capacity A thorough evaluation that achieves a balance between these associated characteristics results in a really optimal PCM selection, which is required to provide better performance and dependability under real-world operating conditions. Hirschey et al. [58] compared the characteristics of salt hydrates with those of paraffin in the same temperature range. According to the findings, salt hydrates having a melting temperature above 20 °C possess greater thermal energy densities of 45–120 kWh/m^3 and lower capacity cost of 1–20 $/kWh, whereas as, paraffin has lower energy density and higher capacity cost of 45–60 kWh/m^3 and 20–30 $/kWh, respectively. For specific applications, paraffins and salt hydrates must be compared in terms of thermal cycling, stability, congruency, corrosion, and supercooling.

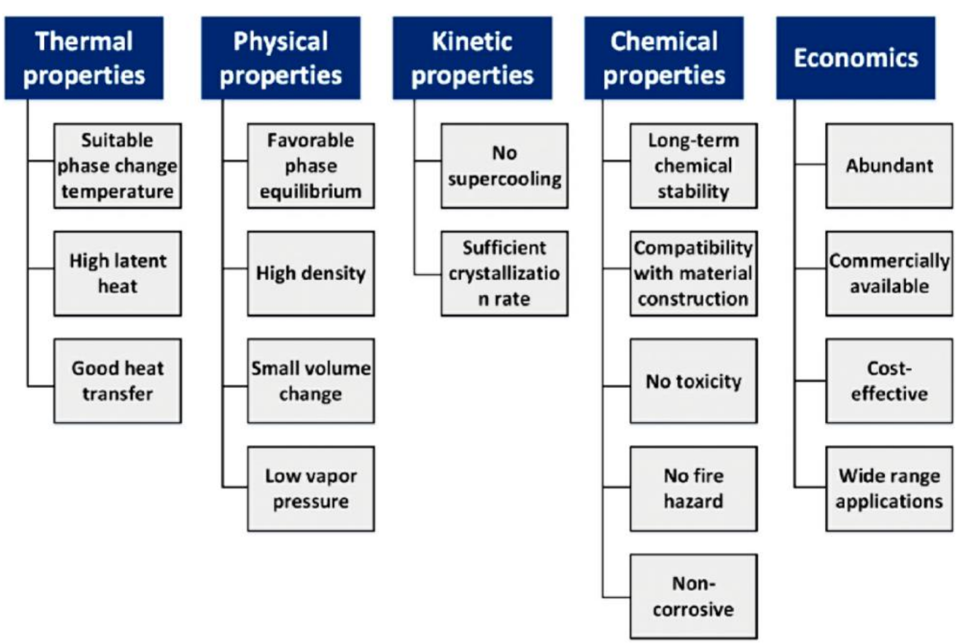

Fig. 5. Schematic representing the PCM selection criteria for HPs [57].

Based on the share percentage of PCMs in HP applications, as depicted in Fig. 4 (b), and the characteristics of different PCMs, paraffin, fatty acids, and salt hydrates are considered as the most suitable PCMs because of their low and moderate costs, as well as commercial HPs operating at low and medium temperatures. Further, Table .2 provides various PCMs that have been employed in HP coupled PCM based TESs.

Despite the fact that several PCM formulations have been proven at the laboratory scale, there are still many obstacles in the way of their actual use in HP coupling. First, most organic PCMs are ineffective because of their limited heat conductivity until they are improved by fins, metal matrices, or nanoparticles, which increase complexity and expense. Second, actual building heating systems require steady performance across several thousand cycles, but the long-term cycling durability of PCMs is restricted to a few or hundred cycles. Third, recurrent freezing-melting issues with salt hydrates and eutectics, such as sub-cooling and separation, might hinder thermal performance. Therefore, these issues need to be thoroughly investigated before adopting and to improve the performance. Standard testing procedures for PCM-TES durability and safety, as well as reliable production techniques for scalable PCM encapsulation, are also desperately needed. Without these developments, PCM-based TES would have difficulty in meeting commercial and policy goals for achieving reliable and sustainable heating.

2.1. Significance of HP combined with the PCM based TES

Numerous experimental and modeling studies and technological optimizations have been conducted to improve the heating/cooling performance and potential of vapor-compression HPs with various thermal sources. These include heat exchange design optimization [71], strategic planning [72], a multistage cycle [73], heat transfer augmentation [74], a nanofluid refrigerants [75], and compressor improvement [76]. Despite these performance-improvement techniques, conventional HPs with various single thermal sources for heating, cooling, and water heating have technical limitations [77,78]. Their year-round operational behavior appeared to be unsatisfactory.

The coupling of PCM-based TES to HPs has significant potential for solving the year-round problem because it allows for a higher percentage of energy-source usage and reduces carbon emissions [79]. The advantages of integrating HPs with latent heat storage systems include lowering power costs, enhancing HP performance, avoiding oscillatory operations, and enabling an HP to run throughout the year at maximum capacity [80]. Seasonal TES has the potential to enhance the performance of HP district heating and establish it as a viable alternative to DH supply [81,82]. The application of HP for space and domestic heating requirements in different seasons using different approaches is depicted in Fig. 6. The space heating and domestic hot water requirements vary according to the seasons. An overview of the annual heating requirements for residential buildings provided by a district heating network under the conventional approach is displayed in Fig. 6 (a). The introduction of energy-efficient heating systems and renovated or modernized buildings has resulted in lower heating requirements, as shown in Fig. 6 (b). Furthermore, Fig. 6 (c) illustrates that the introduction of renewable energy sources into the heating network reduces and shortens the heating requirements for building comfort. Compared to Fig. 6 (b), the summer heating requirements were both shortened and decreased. Owing to the lowest heating demand in summer, solar collectors are the most preferable method for driving district heating networks and can also incorporate solar TES. This approach lowers greenhouse gas emissions and increases the share of renewable energy sources. The heat pump utilizes multiple sources as heat inputs through renewable energy sources and a small amount of supplemental heat from fossil fuels. Finally, Fig. 6 (d) illustrates the heating demand for district heating, which is supplied by the HP in conjunction with renewable energy sources and seasonal TES. In this instance, the heat pump unit runs in tandem with renewable energy sources using multiple heat sources and avoids the need for fossil fuels. Seasonal TES supports the heat pump during winter to operate at the maximum thermal capacity with a high seasonal performance factor throughout the year. Therefore, it is evident that TES coupled with an HP may significantly improve the stability of district heating system operations and reduce energy consumption.

2.2. Integration configuration of PCM based TES to the HP

There are multiple options or configurations for connecting PCM-based TES to HP, such as PCM on the evaporator side for defrosting [84] and the stabilized heat source [85], and PCM on the condenser side for demand-side management or demand load shifting [86].

2.2.1. PCM on condenser side

When the consumer heat demand is intermittent or the HP supply cannot keep up with the peak demand, PCM storage can be used as a backup source of heat. Because the PCM is positioned on the condenser side, the condenser either dissipates excess heat or stores it straight in the PCM, utilizing inexpensive power during periods of low demand and charges for building heating for later use [87]. Ouhammou et al. [88] investigated the heat storage performance from the heat obtained through a condenser HP under different conditions. The findings showed that increasing the condenser power from 5 to 15 kW considerably shortened the PCM charging time by 66 %. PCM having a melting temperature of 44 °C is more suitable for the system. In contrast to

Table 2
PCMs utilized in HP integration and their characteristics.

PCM	Heat Pump Type	Phase transition Temp (°C)	Density (kg/m^3) (solid/liquid)	Thermal Conductivity (W/m·K) (solid/liquid)	Latent Heat (kJ/kg)	Specific Heat (kJ/kg·K) (solid/liquid)	Ref
Paraffin wax (RT5HC)	ASH	5–6	880/763	0.2	245	2.45	[60]
Paraffin wax (RT11HC)	SAHP	11	870	0.2	220	2.2	[61]
Rubitherm	SAHP	31/35/40	789/750	0.18/0.19	170–210	1.8/2.4	[62]
Paraffin wax	GSHP	40–44	785	0.2	240	2.2	[63]
Paraffin wax	SAHP	46.8	940	0.29	212	3.41	[64]
Salt hydrate-based composite	ASHP	47.3–51.4	1320	0.8	218	1.65	[65]
Hydrated salt	ASHP	48	1600/1666	0.45/0.45	170	2.4/2.4	[66]
Paraffin wax + graphite	ASHP	52–54	605	0.85	210	2.4	[67]
Paraffin + expanded graphite	SAHP	53	920	0.8	204	2.1	[68]
A58H + paraffin wax	ASHP + GHP	54–58	839/772	0.25/0.22	243	2.1/1.8	[69]
Myristic acid	GSHP	54	844	1.6/2.7	187	–	[70]

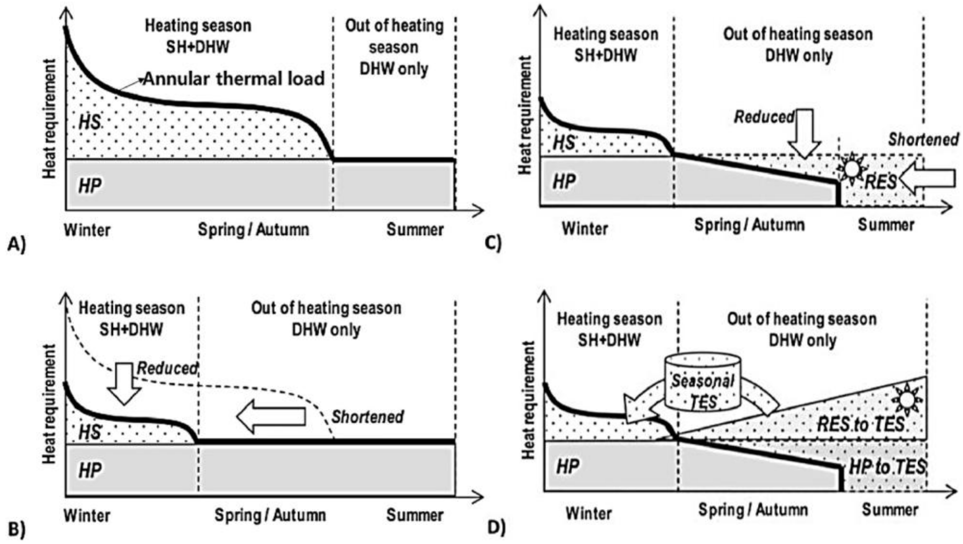

Fig. 6. Schematic representing heating requirement curve for HP connection and operation for district heating under different seasons [83].

conventional sensible storage media, the PCM is the most suitable storage medium for coupled HP-TES because it lowers the electricity usage of the compressor and increases the system energy efficiency. The HP may be turned off during extremely cold climates, which would raise the load peak owing to the additional electrical heating requirement to meet the demand. PCM on the condenser side can reduce the demand on the electrical network by shifting the heat production from the peak time. The utilization of a PCM with a higher thermal storage density would minimize the space occupied by the storage unit and would be economical.

2.2.2. PCM on evaporator side

Heat pump effectiveness decreases during the night and in cold climatic conditions because of a decline in the evaporation temperature. To maintain the HP's constant operating temperature at night or on cold days, the PCM should be positioned between the solar thermal collector and the evaporator side, which leads to a steady-temperature heat source [89]. Thus, the evaporator receives continuous energy without any interruption, and the energy source is renewable [90]. This allows the efficient utilization of energy; minimum energy fluctuations and stabilization of the evaporator temperature may significantly enhance the system performance and improve the operational stability of HP in cold regions [67]. The benefits of this technology include the ability to utilize direct heat from solar collectors for end users and enhance HP evaporation conditions. Yosuf et al. [91] developed an ASHP coupled with a solar thermal system with PCM-based storage to store excess thermal energy during a low-demand period or sunny times and release it during the required period. Compared with the system without PCM storage, the average COP of the ASHP system with PCM storage increased by 6.1 % and 14.0 % on sunny and cloudy days, respectively, demonstrating the ability of the system to efficiently meet the daily hot water demand of the home. A similar study was performed by Zhu et al. [92], and results demonstrated that electricity consumption was approximately 72.8 % of that of an HP alone, and its daily operating costs were only 41.2 % of that of an HP alone, with an average COP of 3.79. Li et al. [93] investigated an SAHP with a phase-change slurry that acted as a heat storage or release medium and heat transfer fluid (HTF) for the photovoltaic thermal (PVT) panel to the HP evaporator loop. The phase-change slurry exhibited greater latent heat, which improved cycle stability and efficiency. The combination of the phase-change slurry on the evaporator-side of HP exhibited a decreased compression and pump power, resulting in an average COP of 4.67, respectively. Using a phase-change slurry as the working and storage medium, a stable high-temperature heat source was produced, which improved the heat exchange in the evaporator and increased the efficiency of the HP cycle.

Frost formation on HPs is also a major issue that results in a reduction in performance and higher energy consumption. Frost may accumulate on the evaporator side, because its surface temperature is lower than the freezing and dew points of the surrounding humid air [94]. Frost formation on the heat exchange surface increases its heat resistance and reduces its heat transfer ability, and the continuous buildup of ice can impede the airflow between the coils. This resulted in a drop in the evaporator temperature, which could hamper the HPs performance and enhance power consumption [95]. Therefore, defrosting should be performed on the evaporator heat exchanger to enhance performance and reduce compressor power [96]. The most common defrosting methods are electric resistance heaters, which drastically increase electricity costs, and the hot gas defrosting method, which reverses the HP cycle, reduces the room comfort level, and negatively impacts performance [97]. Thus, to reduce the energy consumption for defrosting, PCM can also be employed in the evaporator side to defrost the HP [98]. A PCM-based defrosting technique can shorten the defrosting process, minimize temperature swings in the room, accelerate the restoration of space heating, and improve the operational stability of defrosting [99]. Chan et al. [100] investigated three different defrosting technologies: reverse HP cycle, hot-gas bypass, and PMC-based energy storage defrosting. The results demonstrated that PCM-based defrosting exhibited superior performance compared to the two conventional defrosting techniques. PCM defrosting exhibited a shorter defrosting time, which was 75 % and 53 % of the reverse cycle and hot-gas bypass, respectively. The PCM-based defrosting system successfully lowered the energy consumption required for the defrosting process because the defrosting and heat recovery times were shorter than those of the other two defrosting methods. Xu et al. [101] investigated PCM-based defrosting and compared it with a conventional method. The results showed that the use of a PCM storage unit reduced the overall energy required for defrosting by 13.9 %. In the meantime, the compressor defrosting power consumption dropped by 55.8 %, about 396.3 kJ–175.1 kJ, respectively. Therefore, the PCM-based defrosting method may be a suitable option for HP defrosting with a lower energy consumption.

According to available research, condenser-side PCM-TES stabilized the supply temperatures and lessened compressor cycling, which in lab conditions can result in COP increases of 10 %–30 %. Further, the PCM at the evaporator side has a great promise in reducing the fluctuation of evaporator temperature, effect of frost and number of defrost cycles.

Nevertheless, poor PCM thermal conductivity, which limits the rate of energy exchange, is a common barrier for both strategies. Although solutions like metallic foams and PCMs augmented with nanoparticles have been suggested, their commercial viability is still restricted, and the financial implications have not been thoroughly examined. Thus, in order to make the system economical and suitable for commercial use, researchers need concentrate on these areas.

3. Coupling of PCM based TES to the various thermal source vapor compression HPs

3.1. Air-source heat pump (ASHP) with the integration of TES

ASHP delivers heat from low-temperature outdoor air by upgrading the heat process to an indoor environment for space heating of buildings, which is three to five times more effective than electrical heating [102]. Ruan et al. [103] evaluated the performance of an ASHP water-heating system under different operating conditions. It was found that the exergy efficiencies of the compressor and condenser improved with an increase in the air temperature of the evaporator, and an increase in the air flow rate at the inlet of the evaporator resulted in a decrease in the exergy efficiencies of the evaporator and compressor. Hence, efficiency of ASHP mainly depends on the outdoor and indoor temperatures, the greater the difference, the lower the performance. The system's performance would be hampered by operating HP under low temperatures i.e., below −20 °C and their performance will be lowered by 45 % as compared to the system operating under moderate temperatures [104]. In addition to having a reduced efficiency, the exterior surface of the evaporator coil can experience temperatures below the freezing point of water.

Moreover, heat generation was enhanced with an increase in humidity, and as the humidity level exceeded 70–90 %, a further decrease in heat generation was observed in the system. Furthermore, elevated levels of outside humidity have the potential to form ice and water condensation [105], which results in diminished heat transfer because frost reduces thermal conductivity. The accumulation of frost may also lower the airflow rate through the fins, hindering the performance of the evaporator [106]. Owing to the lower heat transfer, the HP was forced to operate under reduced saturation pressure with the evaporator. This may affect the superheating levels, allowing liquid into the compressor and resulting in the shutting down of the HP [107]. Based on these discussions, it was concluded that air temperature, relative humidity, and mass flow rate play a significant role in the HP performance of the system.

Therefore, the application of ASHP has been limited to low-temperature environmental conditions because of their higher compression ratios and decreased heating capability [108]. Numerous advanced technologies, such as ejector-improved vapor injections, multistage compressors, and cascades, have been proposed to enhance performance in cold regions [109,110]. Many advanced ASHP systems have been proposed to enhance the efficiency of ASHP in cold environments. These technologies can enhance the heating performance to some extent, but they also have difficulties that require attention. Combining TES with an ASHP is a promising approach to overcome the abovementioned issues [111,112].

ASHP based water heating systems have attracted significant interest in recent years because of several benefits, including lower maintenance costs, quick installation, high efficiency, and zero waste gas. However, it has certain issues, including longer heating times and rising hot water demands, which increase the demand for TES capacity and performance factor. Therefore, the introduction of TES to ASHP water heating can preheat cold water and shorten the heating duration. Long and Zhu [113] studied a PCM TES combined with an ASHP water-heating system to supply domestic hot water during an off-peak electricity period. A paraffin PCM with a melting temperature of 56 °C was used for storing energy. The refrigerant receives heat from air through an evaporator and compresses it using inexpensive off-peak electricity to form a vaporized refrigerant. Furthermore, the heat absorbed by the refrigerant after compression was released into the PCM through the condenser. The heat stored in the PCM was released to increase the water temperature during peak demand periods, as shown in Fig. 7. Compared with electric-resistant water heaters, PCM-powered water heating, which uses off-peak energy, is far more efficient and requires less space than an ASHP water heating system with a water tank. The average COP of the system was significantly greater than 3.08, making it a viable choice.

Wu et al. [114] developed an ASHP combined with a water storage tank to improve operational efficiency at lower ambient temperatures. The operation of the system involves charging the water storage tank through ASHP during daytime and turning off the ASHP while discharging the thermal energy that has been stored in the storage tank at night. This strategy implies that ASHPs would always run at higher ambient temperatures and turn off at lower temperatures. The observed findings showed that the average daily indoor temperature ranged from 21.0 °C to 23.0 °C, while the average daily outside temperature varied from −9.3 °C to 11.3 °C. In the mixed operating strategy, the ASHP operation period was shorter than that in the conventional continuous operational mode. The water TES tank heating system improved the lower-temperature operating conditions of the ASHP by supplemental heating of the building during the coldest periods of the day. It was found to successfully address the problem of the decreased COP and heating capacity of ASHPs at lower ambient temperatures.

Lin et al. [64] designed and experimentally investigated the performance of an ASHP coupled with a TES under different design and operating parameters. To enhance the system performance in cold climates, a heat exchanger-based TES connected to a condenser is being developed. Furthermore, based on the simulation findings, the melting rate of PCM was accelerated by both increasing the fin thickness and decreasing the fin pitch, although the tube diameter modifications had a minimal effect. The water flow rate must be increased to achieve high release power during the discharging period of the TES. Furthermore, the cascade PCM TES has a 10.08 % shorter charging time and a 4.01 % enhancement in COP compared to the single-PCM TES, and their schematic is shown in Fig. 8. It was concluded that combining an ASHP with a TES is an effective way to increase its utilization at extremely low temperatures.

Shan et al. [115] proposed a latent TES system coupled with the ASHP of a hydronic radiator return line to shift the peak loads. Thermal energy is stored during off-peak demand periods, and the stored energy is retrieved to preheat the incoming air of the evaporator through the TES system during peak demand, as shown in Fig. 9. According to the findings, the TES needs an extra 2.8–13.5 kW of power input during the

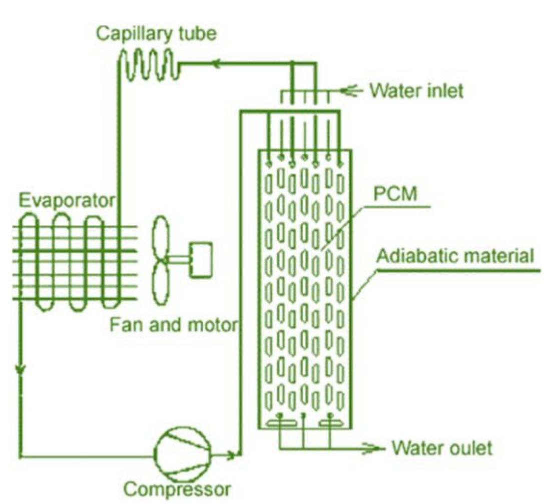

Fig. 7. Working of ASHP with the integration of TES [113].

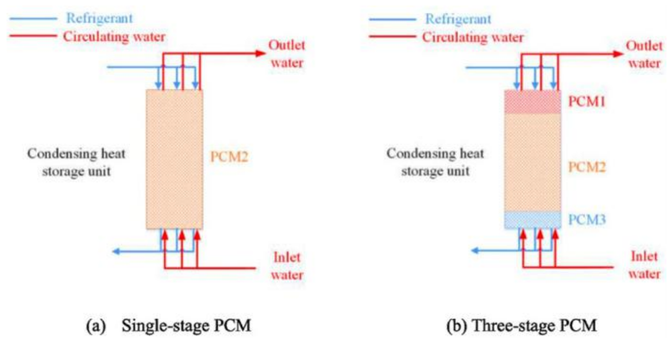

Fig. 8. Schematic of a) single and b) cascade PCM based TES coupled with the ASHP condenser [64].

charging process, and its electricity consumption of 2.8–3.6 kW shifts from on-peak to off-peak hours. The total daily heating expenses are 1.0 %–2.1 % higher than those of the standard system, owing to the constraint of the rating capacity of the HP and ineffective PCM shell-tube TES. The coupled system heating expense is 0.3 %–0.6 % less than that of a standard system in a particular scenario, as the HP can provide all heating demands.

Du et al. [116] developed an energy-efficient ASHP integrated with a PCM-based TES for space heating applications, as depicted in Fig. 10. A salt based PCM was developed with a phase transition temperature of 50 °C, which can match the temperature of HP condenser and building heating applications. Subsequently, an IDHEX with a finned tube was constructed and filled with 70 kg of PCM to serve as both the HP condenser and PCM TES, as shown in Fig. 10. Furthermore, the performance of an ASHP coupled with a PCM TES system was examined under various operating conditions. The findings demonstrate that IDHEX outlet water temperature remains constant between 44 and 47 °C throughout the discharging operation of TES and allowing the fan coil air temperature varying between 34 and 40.5 °C. Under low atmospheric temperatures (5.5–11 °C), the 34 m^2 indoor space was heated to 19 °C. Furthermore, the system exhibits a low operating cost (approximately 15.1 %) compared to a traditional electric heating system and a significant increase in energy efficiency (approximately 151.6 %) compared to traditional TES devices. With energy storage, the developed HP-PCM system exhibits abundant potential for scalability and economical space heating.

Based on the above discussions, it is evident that an ASHP with PCM has proven efficiency improvement as well as a reduction in power consumption and a mismatch between the energy supply and demand with load-shifting strategies. Defrosting is a major issue in ASHP during winter, and the widely used conventional reverse-cycle defrosting approach can address the issue of ASHP icing in winter, which will lead to a suspension of heating in indoor areas while defrosting, which will reduce the thermal comfort of those who live within. To overcome this problem, the integration of PCM into an ASHP can successfully defrost, resulting in an increase in overall efficiency and enhancing the indoor thermal comfort of the building. It was also observed that adopting a cascade PCM system as compared to a single PCM is a more appropriate option for maximizing the energy utilization and shortening the charging time. Moreover, proper selection of a PCM with an appropriate phase transition temperature, design of a storage tank and volume with improved enhanced thermal conductivity or heat transfer, and multi-energy integration with PCM-based energy-stored ASHP are future research advancements in ASHP. Further, Table 3 is provided to summarize the various studies for critical analysis.

Overall, even though laboratory study shows that PCM-based TES can improve ASHP performance, considerable advancements will be needed for progress from lab-scale models to commercially viable systems. These include the establishment of reliable predictive control systems, scalable and affordable techniques to increase PCM thermal conductivity, multi-season performance prototypes in occupied buildings, and standard durability assessment across thousands of freeze-melt cycles. Simultaneously, comprehensive techno-economic analyses and regulatory incentives are necessary to widespread. Particularly in colder areas, PCM coupled HPs have an enormous opportunity to significantly reduce the carbon footprint of residential and commercial heating over the course of the next five to ten years.

3.2. Solar assisted HP (SAHP) with TES

There are several technological methods for increasing the efficiency of ASHP, including the use of an auxiliary source, secondary suction, and insulation of the evaporator [117]. These techniques have some limitations because they can only slightly enhance performance, particularly

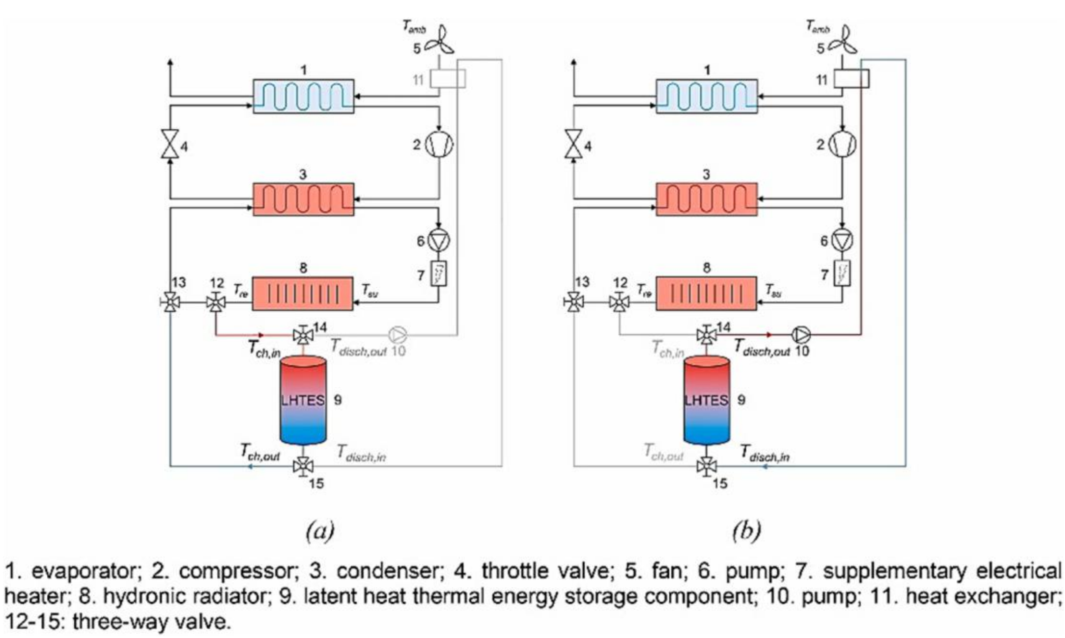

Fig. 9. PCM based TES coupled with HP during a) Charging and b) Discharging [115].

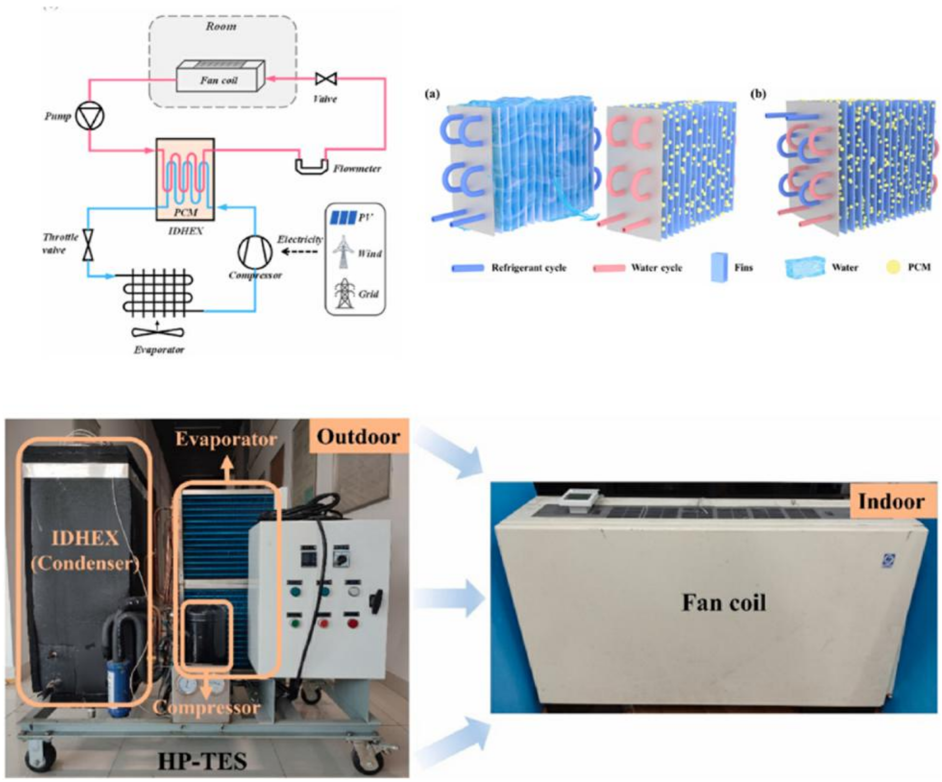

Fig. 10. Schematic showing operating of HP with PCM and experimental setup [116].

Table 3
Summary and critical evaluation of PCM-TES integrated with ASHP systems

Approach	Findings	Strengths	Limitations
PCM is located on the condenser side. Long & Zhu [113]	COP >3	Simple concept: charging TES using condenser heat	Limited test durations, no field data, and unclear PCM cycle durability
PCM is located on the evaporator side Chan et al. [100]	Reduced defrosting time by up to 75 %	Enhanced comfort and uses lower energy to defrost.	Encapsulation and PCM solid-melting cycles have not been studied.
Hybrid PCM-water TES Wu et al. [114]	Increased capacity factor and load shifting at night	Hybrid water and PCM TES are used to buffer loads.	Problems with thermal stratification and the possibility of PCM sedimentation
Cascade based PCM TES. Lin et al. [64]	Shorter charging times and improved energy utilization	Optimizes and maximizes the storage of PCM	More intricate; uncertain control method; undisclosed cost
PCM is located on the condenser side Du et al. [116]	Better energy density and 1.5 × baseline COP,	High latent energy	Supercooling, phase segregation and Corrosion, issues

under harsh weather conditions. Furthermore, certain techniques, such as the use of a supplementary heater, consume more energy to ensure excellent performance. Therefore, researchers have introduced the solar-aided HP (SAHP) system to address these issues [118]. Solar-aided HPs can be connected to PV arrays, solar thermal collectors, or both. The SAHP system comprises a PV or solar thermal collector as the thermal source for the evaporator, compressor, throttling valve, and condenser for heat exchange with the end users. The thermal collector converts solar radiance into thermal energy, which is supplied to the HP system for district heating applications [119].

Based on the type of integration and generation, the system was classified into direct and indirect type SAHP [120,121]. In the direct-expansion system, the HP and thermal collector form a single unit, and the solar thermal collector functions as an evaporator, as shown in Fig. 11 (a). In this system, the refrigerant flows directly through the solar collector and absorbs the incident solar thermal energy, thereby providing a high-temperature vapor refrigerant [122]. For the indirect expansion system, the HP and solar collector were separated and operated independently [123], as shown in Fig. 11 (b). A solar thermal system utilizes either water or air heated by a solar collector to transfer heat to the evaporator. Indirect systems are classified into three categories: series, parallel, and complex or dual-source systems [124]. By interconnecting the solar thermal collector and HP in series with the aid of a heat exchanger, the series system transferred solar thermal energy to the HP evaporator and a greater COP is obtained as the heat exchanger functions as an HP evaporator owing to its higher temperature compared with the conventional ASHP [125].

In a parallel system, the HP is not supported by the solar thermal system as a heat source for the HP evaporator, and the solar thermal system and HP are connected in parallel and operate independently. The heat generated from the solar thermal system is directly delivered to the space heating of buildings without interacting with HP, as shown in Fig. 11 (c). The HP is the main system, and as the solar radiation is insufficient to generate heat, then the HP will start to operate for delivering heat energy to the space heating of buildings. Under ample solar radiation and ambient temperature, the parallel arrangement improves the performance of the indirect HP system [126].

The dual-source SAHP system has two sources: solar thermal energy from the collector as the heat source and ambient temperature, as shown in Fig. 11 (d). The first evaporator of the HP was connected to the solar thermal system through a heat exchanger for the heat source, similar to a series system. The second evaporator was located outside, and ambient air was used as the heat source. To maximize the benefit of the heat source with the highest temperature, the HP would have obtained energy either from solar or ambient air, depending on which offered a

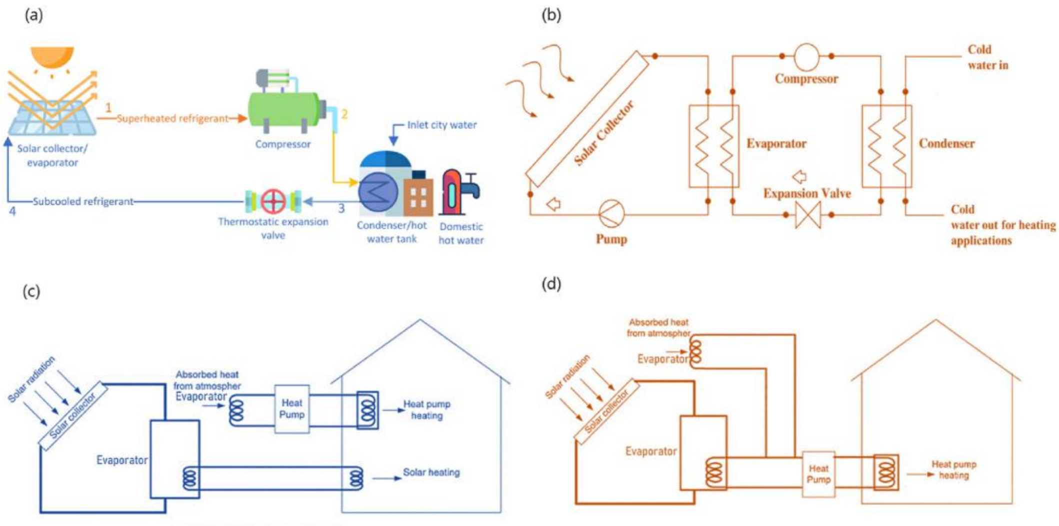

Fig. 11. Schematic of a) direct b) indirect series c) indirect parallel d) dual source expansion SAHP [128–130].

better COP [127]. Furthermore, direct expansion systems have recently received significant attention owing to their many advantages such as fewer components, reduced heat loss, and minimization of the chance of corrosion and deterioration from water in the heat exchanger. However, the thermal efficiency of the system is directly related to the variations in the intensity of solar radiation, which is a drawback of DX-SAHP. The variation in solar radiation from morning to evening can cause significant fluctuations in system performance.

3.2.1. Challenges of SAHP

Although several researchers have contributed significantly to progress in the technology of SAHP systems, certain issues and difficulties persist**.** Solar energy can play a significant role in global decarbonization in the crisis of fossil fuel energy scarcity and climate change. The share of renewable energy generation has also increased, and its proportion is steadily increasing to achieve energy sustainability [131]. Utilizing air and solar energy sources in tandem is a significant problem for SA-ASHP systems owing to the apparent climatic variations across different places and seasons [132]. Therefore, the imbalance between an unstable heat source and the constant heat demand can be effectively resolved by integrating an energy storage system [133]. Developing economical and practical methods to improve energy storage systems is also challenging for researchers.

To increase the energy efficiency of SA-ASHP systems, the design parameters and control methods must be adapted to regional environmental conditions. The performance of an SA-ASHP system is significantly affected by design factors such as the compressor speed, solar collector area, and thermal storage tank size [134]. Furthermore, the performances of SA-ASHP systems are affected by three environmental factors: humidity, ambient temperature, and solar radiation [135]. Consequently, under varied climatic conditions, it is imperative to investigate the technological difficulties of the SA-ASHP, as shown in Fig. 12.

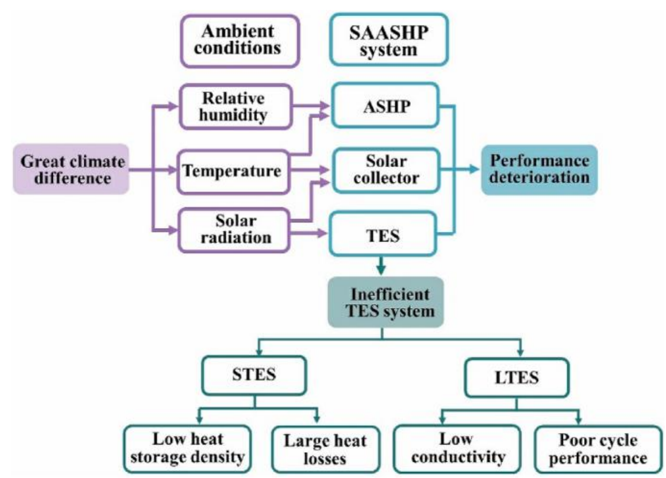

Fig. 12. Technical difficulties encountered by SA-ASHP [136].

3.2.1.1. Effect of environmental conditions on SAHP performance. The maximum temperature of the SA-ASHP system achieved by the solar collector was directly influenced by the intensity of the solar radiation. In the direct-expansion SA-ASHP system, the COP decreased by 14.5 % as the solar radiation was lowered from 500 W/m^2 to 100 W/m^2. Furthermore, the COP of the indirect-expansion SA-ASHP could be enhanced by 5.2 % as the solar radiation increased from 0 to 500 W/m^2. Hence, it is challenging for SA-ASHP systems to harness the maximum solar radiation energy [137]. Ghasemipour et al. [128] performed a comparative study of two different direct expansion systems, solar-assisted and air-sourced HP, under the same conditions. The effects of climate on the performances of the two systems were evaluated under various conditions, including ambient temperature, solar radiance, evaporator or collector area, compressor speed, and wind speed. The findings for the two HP water-heating systems demonstrate that weather (varying months) has a major impact on the annual performance. Under the specific circumstances of the case study with mild weather, changes in solar radiance, ambient temperature, and wind speed throughout the year can increase the COP by up to 33 %.

The coupling of parabolic collectors and evacuated tube collectors can also result in a higher temperature under lower solar radiation, which leads to an improvement in the COP of the system [138]. Both the HP and the solar collector are affected by the surrounding temperature. As the ambient temperature decreased, the temperature differential between the collector and its surroundings increased, resulting in an increase in thermal loss and a decrease in thermal efficiency [139]. Therefore, proper insulation should be provided for minimizing the heat losses in system. A major issue that must be resolved is the effective utilization of solar and air sources, which enhances the performance of SA-ASHP systems under unfavorable environmental conditions.

One of the most intriguing solar energy conversion technologies is the photovoltaic-thermal (PVT) collector, which combines the generation of thermal and electrical energies in one unit [140]. Integrating a photovoltaic-thermal collector and HP technologies can meet a significant portion of a building's thermal energy and electricity needs through renewable energy sources and enhance the performance of the HP and collector [141]. The PVT collector generates heat, which must be eliminated because it affects performance and reduces electricity production. Therefore, the rejected heat from PVT cooling can be used as a heat source in the evaporator to increase the temperature. This cooling and heat rejected by the PVT will have a combined positive effect on the increase in both the PVT and HP performance [142]. In addition to the benefits for the individual subsystems, several studies conducted over the past ten years have shown that PVT-SAHP systems may significantly improve the overall energy performance compared to conventional SAHP systems that use air-source HP and solar thermal collectors [143, 144]. Several studies have proven that although the heat collected and transferred to the HP is somewhat lower, a greater amount of renewable power, an improved seasonal performance factor, and greater overall energy performance can be achieved compared to other SAHP systems [145,146]. Energy storage is an additional essential part of PVT-SAHP, and it minimizes the discrepancy between the thermal energy and the building load profile [147]. PCM and water-based TESs are extensively used in PVT-SAHP systems, demonstrating their significance from both the source and user perspectives. TES can improve solar energy output, HP performance, and solar constant heat supply between the PVT system and HP [148,149].

Zanetti et al. [150] conducted an experimental investigation of a direct-expansion dual-source HP using Co_2 as the refrigerant. The evaporator of the HP prototype can be either a PVT solar collector or an air-finned coil heat exchanger. The HP was operated under dynamic conditions during both the air- and solar-mode experiments. The exploitation of heat from PVT collectors leads to a cooling impact through refrigerant evaporation in the collectors and causes an 8 % improvement in photovoltaic power generation. It was concluded that the dual-source PVT-HP system enhanced the HP performance and electricity output of the PVT. Wang et al. [151] developed a PVT-dual-source HP with the integration of a PCM-based TES. A TRNSYS simulation model was established to assess the system economics, energy efficiency, and thermal performance. The PCM storage performance was compared with that of water storage, and the impact of various PCMs on the system parameters was also examined. The findings demonstrate that, in comparison to a traditional gas boiler system, the associated system exhibits a seasonal performance factor of 2.3, 56 % decrease in energy consumption, and 27.7 % reduction in operating expenses. Further, the developed system showed a maximum COP of 3.2 and while, water source HP had 2.8, respectively. The PCM-based storage system exhibited better performance and long-term reliability than water-based storage systems. It was concluded that higher-density PCMs were advantageous for enhancing the overall performance of the system. Therefore, the integration of TES with PVT-SAHP offers an intriguing solution to the net-zero energy-efficient building design and able to meet all building thermal requirements and also improves the significant share of renewable energy. Among the various PVT-SAHP configurations currently available, the dual-source indirect-expansion system is the most promising option for fulfilling all building thermal requirements. This system is an advancement over single-source and direct-expansion systems and lacks the primary disadvantages that restrict its utilization.

Choi and Choi [152]. evaluated the performance of a novel PVT air collector coupled with an SAHP under different operating and geometrical parameters. Triangular blocks were incorporated into the PVT air heater to enhance its thermal efficiency and boost the effectiveness of the HP, as depicted in Fig. 13. The performance of the system was investigated by considering the mass flow rate of air, PVT air-heater area, solar intensity, ambient temperature, and intake water temperature. An increase in the flow rate, PVT area of the air heater, ambient temperature, and solar radiance resulted in a higher heating capacity and COP. The PVT air heater power generation surpassed the system power requirement, allowing the PVT-SAHP to function independently under all flow rates without the need for grid power, whereas the ASHP required power from the grid to drive the compressor, which is shown as a negative value in the profile in Fig. 14. At all inlet water temperatures, the PVT-SAHP outperformed the ASHP system and exhibited a COP that was 4.55 %–13.25 % more than that of the ASHP system, as shown in Fig. 14.

Gao et al. [153] investigated the performance enhancement of

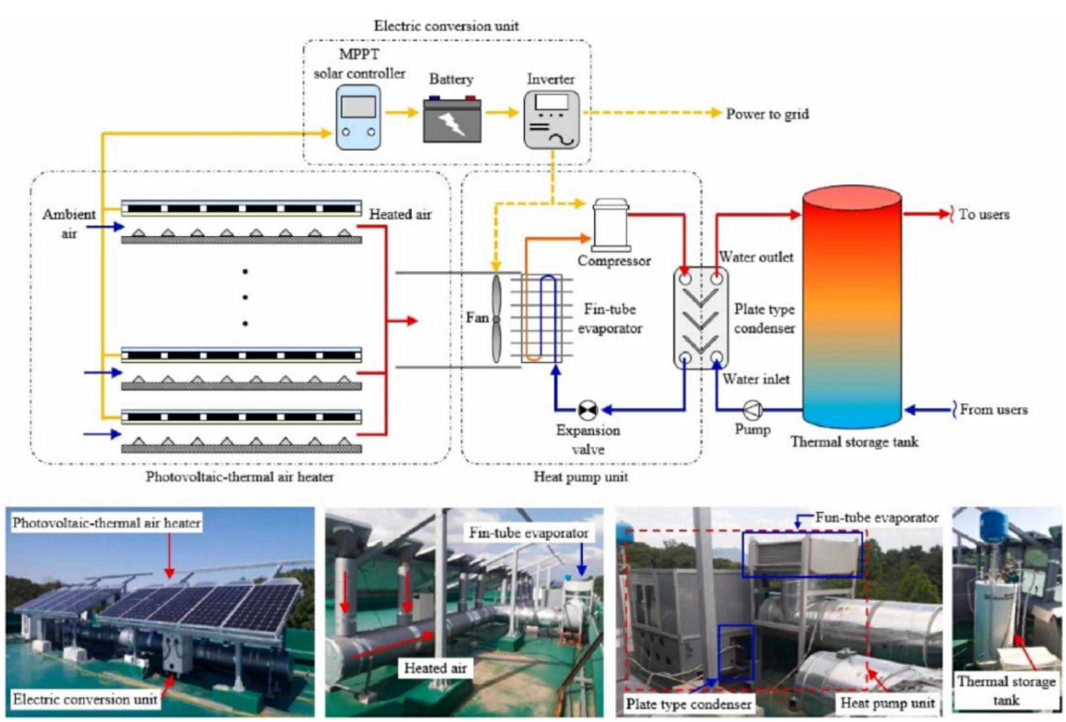

Fig. 13. Schematic of PVT air heater with the integration of SAHP [152].

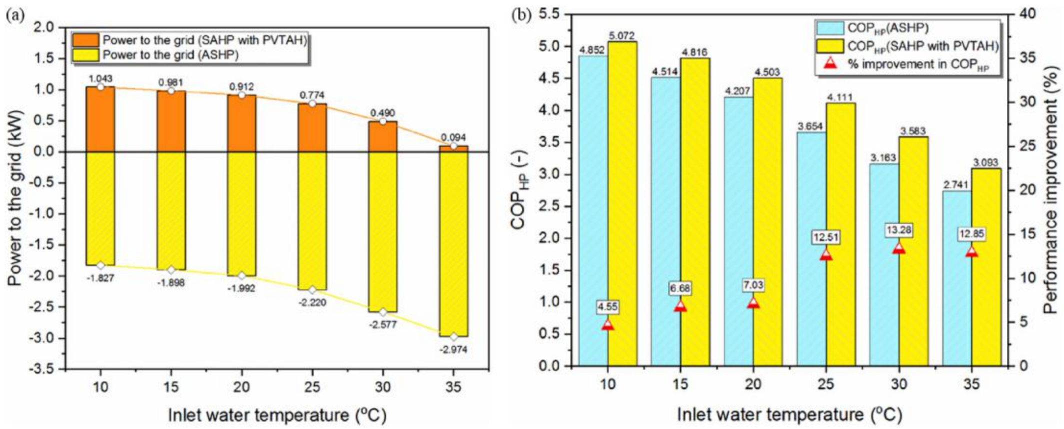

Fig. 14. Effect of inlet temperature on power to the grid and COP for different systems [152].

dual-source air and solar HP with the coupling of a PCM TES, as shown in Fig. 15 (a), and developed control strategies for effective operation. The PCM is filled around the condenser coil to store solar energy. The system functions under the following four typical configurations based on the wintertime ambient temperature in the extreme cold region: a) Heating solely with solar energy: In the first scenario, HP is turned off as long as solar radiation is sufficient to heat the building, supply hot water, and store energy; b) heating in conjunction with solar energy and HP: a portion of the solar energy and HP condensation heat is stored in the condenser thermal accumulator, while the building domestic hot water and heating are provided by the remaining solar energy combined with the sub cooler's waste heat; c) Heating by HP alone: In this case, HP is turned on as the solar source is not available. In this process, the heat obtained from the HP condenser is stored in a thermal accumulator, whereas the waste heat released by the sub cooler is used to supply hot water and domestic heating for buildings. d) Condenser thermal accumulator: If the HP or solar energy is unable to sufficiently power the system, the heat that had been stored in the thermal accumulator is discharged to supply heating or domestic hot water for the building. Considering the four typical operating methods, the combined heating system can provide buildings with constant heating requirements even during extremely cold winters. It was observed that increasing the flow rate of the solar water supply increases the amount of heat stored by solar energy and decreases the compressor power consumption, resulting in greater COPs. In real-life situations, it is recommended to use a higher water flow rate to maximize efficiency and reduce energy consumption by increasing the share of the solar energy supply. Reduced energy storage time and an increase in the system condensation temperature are the outcomes of an increase in the overall heat storage power. However, the increased power consumption of the compressor resulted in a decrease in the COPs. Achieving an optimal balance between the energy efficiency of the system and heat storage period in accordance with the demands and conditions is essential for practical applications. Zhang et al. [154] also developed a dual-source indirect expansion SA-ASHP with the coupling of a hybrid TES, as depicted in Fig. 15 (b), and optimized the control strategies for enhancing the performance. The hybrid TES tank comprises horizontal tubes embedded with paraffin as the PCM and water as both the sensible storage material and HTF. Furthermore, the increased evaporator temperature due to the TES causes a notable improvement in the efficient functioning of the solar HP mode. The average COP and heating capacity of the solar HP mode were 36.5 % and 50.0 % higher than those of the ASHP mode, respectively.

Zheng et al. [155] compared the performance of SA-ASHP PCM floor heating with conventional radiant heating using TRNSYS. A residential building located in Tianjin was chosen as the simulated scenario to assess the energy consumption, heating capacity, and economic impact. The energy usage of the system during the heating season decreased by 35.7 % compared to that without a PCM floor, and the yearly CO_2 emission reduction increased from 1535 kg to 2762 kg. Owing to the decrease in energy usage, the COP of the SA-ASHP rises from 3.49 to 5.43, respectively.

Yıldız et al. [156] experimentally evaluated the thermal performance of a SAHP with the integration of TES. Three different TES tank temperatures, with and without PCM, and four flow rates through the condenser ranging from 400 to 1200 L/h were investigated. The experimental data were used to determine the COP, compressor operation time ratio, overall heating time, and temperature of the tank. It was seen from the findings that the PCM addition can have a negative effect at TES temperature 55 °C, but at 35 °C, it can greatly enhance the heating time up to 30.6 % and COP up to 33.9 %, respectively. This study revealed that the utilization of PCMs in HP TES tanks may be ineffective because sensible heat storage accounts for a large portion. Conversely, when PCMs are incorporated with sensible heat storage through reduced temperature differentials, efficiency and effective energy usage are enhanced.

Gao et al. [157] investigated a solar PVT coupled with an HP and an evaporative PCM-based accumulator. An experimental setup was designed, as shown in Fig. 16, to assess the impact of two different heat transfer media (water and PCM slurry) and investigate the performance of the evaporative PCM-based thermal accumulator. The experimental findings showed that using a phase-change slurry as an HTF improved the power-generation efficiency of the PVT system by 2.71 % compared with using water as an HTF-based system. The phase change slurry enhanced the evaporation temperature of the evaporator, which boosted the efficiency of the HP cycle. An average COP of 4.7 was exhibited for a HP, which was 43.46 % higher than that of water as an HTF. Furthermore, PVT coupled HP with an evaporative PCM system exhibited an average COP of 8.23, which is a substantial increment of 57.36 % compared to water as a fluid. Furthermore, the evaporative thermal storage unit with a phase-change slurry exhibited superior thermal storage performance owing to its high-temperature stratification and reduced temperature drop throughout the heat release process. It was concluded that employing a phase-change slurry in SAHP systems is feasible and has considerable potential.

Several researchers have focused on serial, parallel, and combination setups to obtain optimal performance. Among all the configurations, the dual-source and PVT-HP exhibited superior performance by providing both the electricity and heating demands of buildings. It also enhances electricity productivity by cooling the PVT panels, maintaining the optimal panel temperature and causing a significant increase in power production. Furthermore, the integration of PCM-based TES with dual-source HP enhances the COP and provides a consistent heat source to the HP during nighttime with minimum energy consumption. The

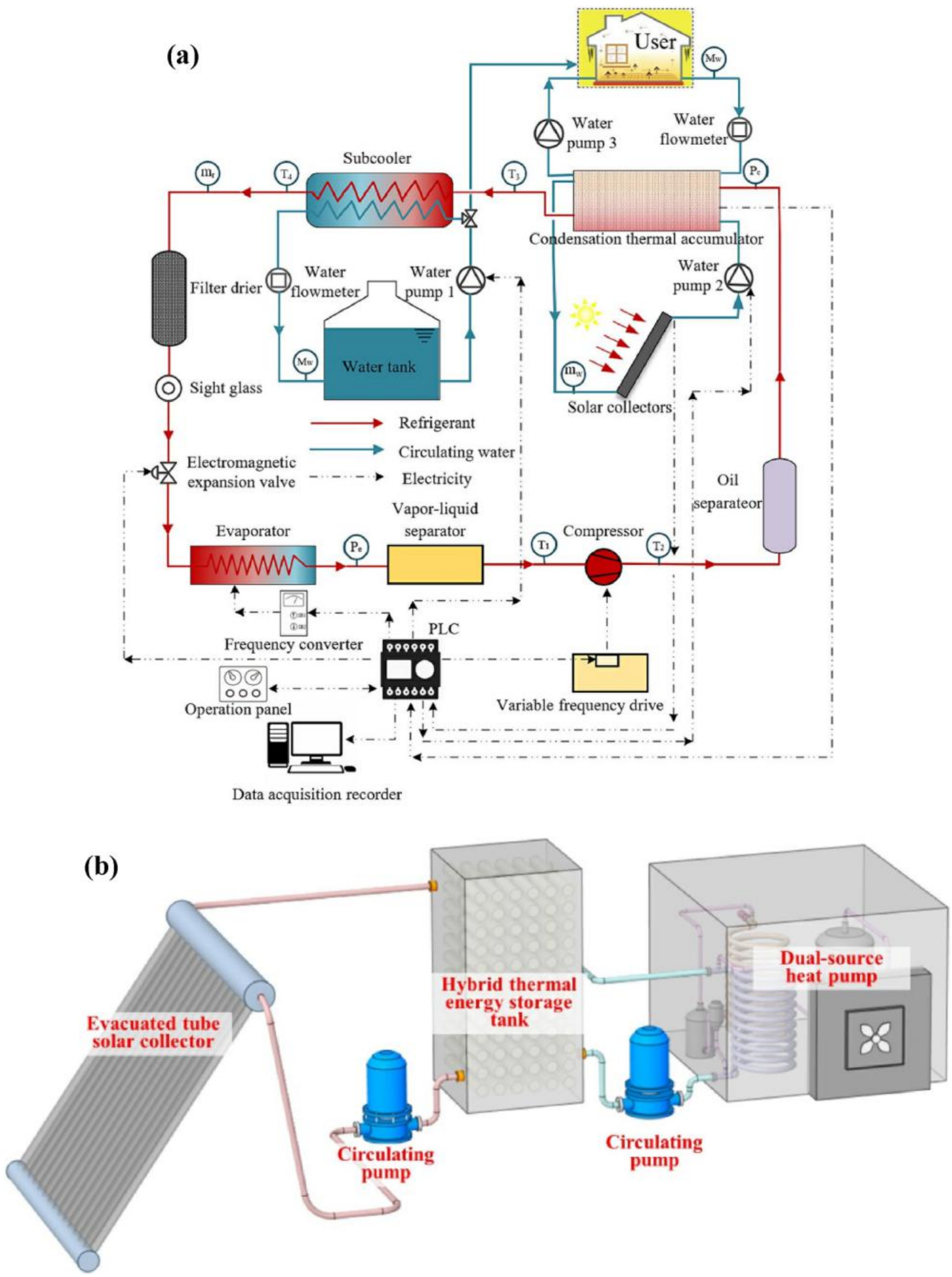

Fig. 15. Schematic of dual source HP integrated with a) PCM and b) Hybrid based TES [153,154].

integration of combined sensible-latent TES will be a suitable solution for HP because of the constant supply of the heat source, faster change, and provision of thermal energy for a longer period. Moreover, to enhance the heat transfer ability of PVT collectors and thermal storage, researchers have developed a novel phase-change slurry that acts as both an HTF and storage medium. This phase-change slurry showed a significant improvement in thermal performance compared with water and air. One of the main concerns with this slurry is the pumping power, which should be considered because the slurry may consume high pumping power. Therefore, further research should focus on the phase-change slurry in PCM-based PVT and dual-source HPs. Table 4 provides a summary of the presented studies, emphasizing performance indicators, benefits, drawbacks, and current technological preparedness in order to evaluate SAHP–PCM TES combinations in a methodical manner. These studies reported that COP and seasonal performance factors (SPF) show encouraging efficiency improvement across configurations and range from 2.5 to 5.5, receptively with the combination of PCM based TES.

It is evident that PCM-based TES enhances defrost control, seasonal performance parameters, and heat pump cycling stability. The lack of thorough, multi-season field tests to confirm these advantages in actual building and climate circumstances is a significant drawback. The scalability and cost predictability of PCM-enhanced SAHP systems are still unknown in the absence of this evidence. In the next five to ten years, SAHP systems with PCM-based TES and advanced controls may establish themselves as a fundamental component of net-zero energy buildings.

3.2.1.2. Enhancement of solar thermal collectors and TES utilization

3.2.1.2.1. Solar thermal collectors with PCM. Conventional solar thermal collectors exhibit poor thermal performance and cannot utilize the maximum solar energy. Therefore, to enhance solar energy utilization, researchers have developed techniques that directly incorporate PCMs into solar thermal collectors [158]. PCM introduction in PVT

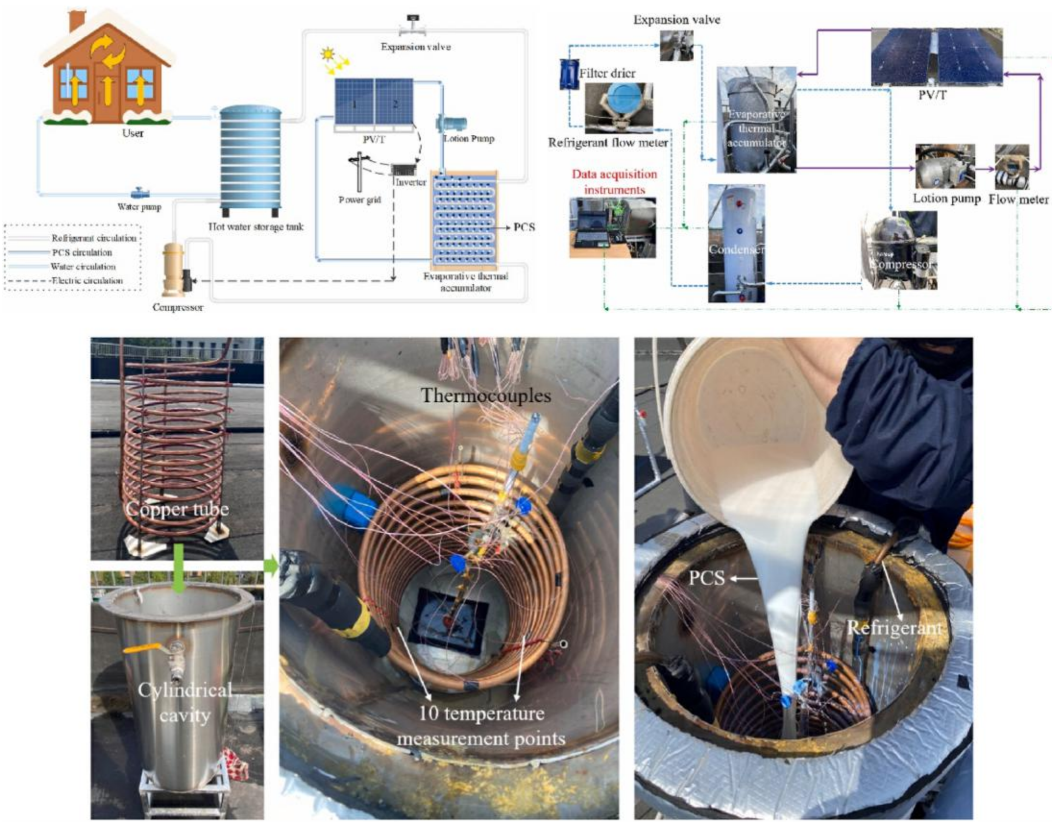

Fig. 16. Schematic and experimental components of PVT- SAHP with PCM storage [157].

Table 4
Summary and comprehensive analysis of SAHP-PCM TES

HP Configuration	Reported COP/ SPF	Key Benefits	Performance Enhancements	Limitations	Commentary
Direct-expansion SAHP + PCM	COP 2.5–3.5; seasonal COP ~2.8	Simple structure; fewer components, very efficient because of reduced losses, Lowe cost	Less need for backup heaters and easier construction	High performance fluctuation due to solar variation and risk of thermal choking	Effective PCM control is required to manage solar diurnal fluctuations.
Indirect series SAHP + PCM	COP 3.0–4.0; seasonal SPF up to 3.5	Stabilizes evaporator temperatures; Simple, inexpensive, and easy to retrofit higher COP	Decreases compressor cycling and increases solar utilization hours.	Complicated plumbing; untested PCM durability in a solar loop	Perfect for collector space retrofits
Indirect parallel SAHP + PCM	COP 2.8–3.8; seasonal SPF 3–3.5	Flexibility in operation; decoupling of HP and solar thermal system, moderate cost	Steady heating supply and a higher percentage of solar energy harnessing	Tank size issues and inadequate utilization of PCM during low sun hours	Suitable for moderate and stable climates
Dual-source SAHP + PCM	COP 3.5–5.0; seasonal SPF 3.5–4.5	Source switching flexibility; optimal seasonal COP	Seasonal COP growth of up to 50 % in comparison to ASHP	More expensive installation; intricate control algorithms	Advanced technology and predictive controls are crucial.
PVT-SAHP + PCM TES	COP 3.5–4.7; seasonal SPF up to 5.0	Both heat and electricity are provided and have net-zero potential	Stabilizing the temperature of PV panels increases their electrical and thermal yield.	Energy pumping for slurries: financial and spatial limitations	Extreme promise for buildings with net-zero energy

systems will be more beneficial by providing the cooling effect of the panel, which leads to an increase in power, and the heat rejected from the PCM will be used for domestic heating or HP applications [159]. Khanlari et al. [160] conducted a study on extending the solar collector utilization period by adding a PCM to the absorber plate. The results demonstrated that embedding the PCM in the solar collector increased the utilization period of the collector, which could result in effective utilization of solar energy. Wang et al. [161] compared a conventional solar collector with a novel solar collector embedded in PCM. The findings showed that the PCM-embedded solar collector exhibited higher and steadier HTF temperatures under low solar radiation than the conventional collector. Bejan et al. [162] performed a comparative study of solar collectors with and without PCM incorporation. Based on these findings, the inclusion of PCM in solar collectors boosted the collectors' overall efficiency by 10.6 %, extended its operating hours by 110 %, and raised its temperature by 8.8 % compared to the collector without PCM. Palacio et al. [163] also performed similar studies, and their findings showed that the performance of the solar collector was significantly affected by the use of PCM for thermal storage. The collector with the PCM had slightly lower daytime and higher nighttime temperatures. This is because the addition of PCM stores energy in the PCM, which causes lower useable heat throughout the day. However, PCMs stored energy also serves as a source of heat energy for space heating applications at night, without interruption. Based on these discussions, it is evident that the addition of a PCM to the absorber plate of a collector increases the utilization of energy and extends the usage period of the collector. However, it is limited to a shorter period, which hinders its application. To operate the system for a longer period and utilize solar energy effectively, an effective TES system must be integrated with the solar thermal collector of the SAHP.

3.2.1.2.2. Improvements of PCM based TES. As discussed previously, latent TES has received increasing attention and has been adopted in SAHP applications. Two types of storage containers are commonly used in latent TES: tubes in shells and packed beds [164]. The tube-in-the-shell TES uses PCMs on the shell side and an HTF flowing through the tubes, as shown in Fig. 17 (a); water-heating applications are usually included in this type of arrangement. The packed bed uses encapsulated PCMs in a cylindrical container, and the HTF flows over the packed-bed-encapsulated PCMs to transfer thermal energy [165], as shown in Fig. 17 (b). Because of their adaptability, encapsulated storage systems can be employed in both air- and water-heating systems [166]. The heat transfer rate plays a crucial role in the development of PCM-based TES systems to maximize system performance. Thermal performance enhancement techniques have attracted increasing interest owing to PCMs' low thermal conductivity. The introduction of fins, porous materials, and nanoparticles increases heat transfer; however, these techniques increase system complexity and cost [167]. In contrast to conventional performance improvement techniques, the cascading PCMs methodology does not change the characteristics of the PCM and prevents the requirement of costly enhancement techniques [168]. Thus, the cascading approach of PCMs is less costly for increasing the heat transfer rate and energy storage capacity. A cascade consists of two or more PCMs in a single storage tank arranged in decreasing order of the PCM melting temperature, as shown in Fig. 17 (c). The main objective was to improve the thermal performance of the system by maintaining a relatively constant temperature differential between the PCMs and HTF during the energy storage and recovery processes. Lower HTF temperatures are sufficient to melt PCMs owing to the lower melting temperature near the bottom of the storage tank. This leads to a more efficient use of thermal energy in the cascade than in the TES of a single PCM. Compared with single-PCM TES, cascade latent storage exhibits superior heat transport, resulting in a reduced charging time as well as a larger heat storage capacity [169].

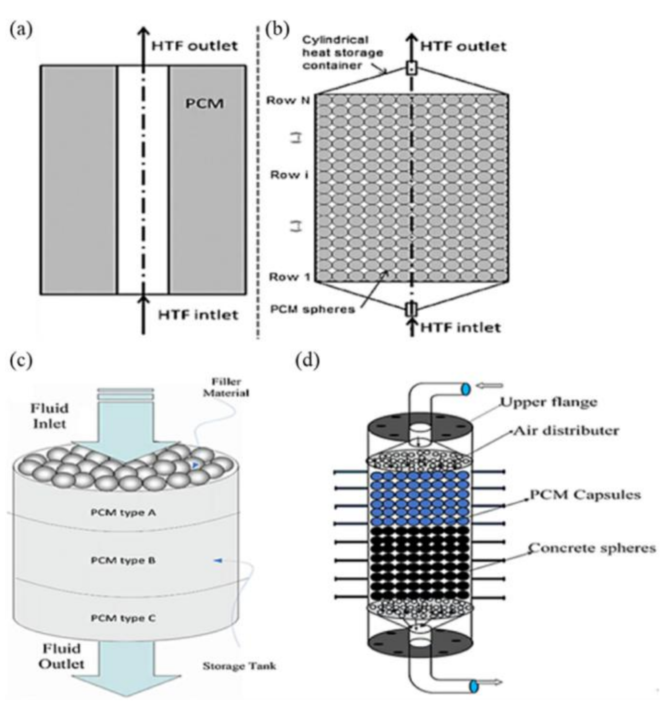

Fig. 17. Different configurations of latent TES a) Tube in shell b) Packed bed c) Cascade and d) Combined [173–175].

In the aforementioned discussion, the benefits and disadvantages of both sensible and PCM-based latent TES systems were discussed. Owing to the lower energy density of the sensible material, a greater volume of storage material is required to store the same quantity of energy stored in the PCM-based system, which causes an increase in the size of the container, leading to an increase in the cost of the container as well as higher thermal losses. To maximize the benefits and minimize the drawbacks of both systems, a hybrid sensible-latent TES system was developed [170], as illustrated in Fig. 17 (d). The advantages of the combined sensible-latent TES system [171,172] are as follows.

I. Increased energy storage capacity compared to the sensible storage system.
II. Constant temperature of HTFs during energy storage and recovery processes
III. Compact and easy installation at less space for SAHP.
IV. Superior rate of heat transfer in comparison to latent storage.
V. A reduced rate of thermocline declines and extended energy usage compared with sensible storage.

Therefore, it is confirmed that integrating the cascade and combined TES system will enhance the performance of the system and utilize the energy effectively for a longer period of time for end user applications. Hence, it is recommended that cascade and combined sensible-latent TES can be integrated into SAHP to improve the COP and operate for longer durations at night for space heating of buildings.

3.3. Water source heat pump (WSHP) with TES

Over the past several years, water-source heat pump (WSHP) technology has emerged as a potential source of energy for heating applications in buildings [176]. The WSHP system has gained considerable interest owing to its benefits, which include producing clean renewable energy, maintaining a reasonably constant water temperature, and enhancing heat exchanger efficiency with high-density water [177]. When using traditional ASHP to heat or cool buildings, water sources offer more comfortable temperature conditions than air sources [178]. Buildings close to surface water bodies such as ponds, lakes, rivers, raw water, and the sea may benefit from exploiting these water sources as sinks and heat sources [179]. These reservoirs contain water that is typically warmer in winter and colder in summer than the surrounding air, which may result in energy savings. Consequently, several studies have been conducted to evaluate the potential of WSHP coupled with various water bodies.

Cardemil et al. [180 investigated the use of a WSHP connected to a domiciliary pool for heating as shown in Fig. 18. The impact of various design factors on the system performance was evaluated using parametric analysis. These findings demonstrate that using an outdoor pool as a heat source is beneficial and not associated with a significant risk of ice development in the pool. Larger buildings, in particular, benefit from shorter system operation times by considering a greater pool area and higher nominal heating capacity. Zheng et al. [181] investigated a seat water source HP using a helical coil heat exchanger and beach well intake system. The performances of the WSHP and ASHP under severely

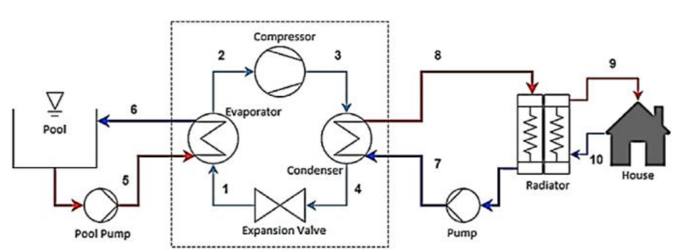

Fig. 18. Schematic of pool water source for WSHP [180].

cold climate conditions were experimentally compared. The findings showed that beach well WSHP had the best performance with extreme cold temperatures throughout the winter for the heating season. Frost development on the surface of the ASHP heat exchanger and ice on the outside surfaces of the helical coil tubes have a significant impact on the heat transfer performance and decrease performance. Although a beach well has a higher thermal performance than a helical coil, developing a beach well requires more rigorous geological conditions and is not economically as favorable as a helical coil. In their investigation, Büyükalaca et al. [182] compared the performance characteristics of an ASHP with those of a river water source, HP. The results of these studies indicate that the river water source HP outperforms the air source HP in terms of cooling COP by 35 %–40 % and heating COP by 15 %–40 %.

Jung et al. [183] examined the performance of a WSHP system under three design considerations: 1) building type, 2) water source type, and 3) water intake distance. The system evaluated the critical parameters in terms of economic, environmental, and energy aspects. Different water sources, such as rivers, the deep sea, raw water, and underground water sources, were considered. Based on the heating to cooling demand ratio (HCR), the building type was classified into five categories, as stated in: HCR $\sim$ 0: buildings with solely cooling demand requirements; HCR $<$1: needs more cooling than the heating; HCR $\sim$ 1: HCR $\sim$ 1: need the same quantities of both heating and cooling; HCR $>$1: need more heating than cooling; and HCR $\sim\infty$: that need only heating in the winter. The distance of the system from the water body, known as the water intake distance, can be classified into two categories: vertical depth and horizontal length. The vertical values were in the range of 0–50 m, and the horizontal lengths were in the range of 100–900 m. The type of water source has a significant impact on the amount of energy saved. Furthermore, each water source exhibited a positive energy-saving rate that improved as the water temperature stabilized. According to their overview, buildings with extended cooling times should use as cold water as possible, whereas buildings with extended heating periods should use as hot water as possible. Underground water is often considered the most suitable for these circumstances. Although the seawater source maintained a steady temperature, it consumed a comparatively large quantity of energy because the water intake system drove the deep-sea water down to 1000 m. The primary energy consumption declined by an average of 1.3–5.7 % for every 100m in both the horizontal and vertical depth distances. Their findings revealed that water source selection had a greater impact on carbon emissions and energy savings than building type. This type of building is expected to have the greatest impact on economic viability. All parameters related to energy, environmental, and economic feasibility were significantly affected by the water intake distance, particularly the vertical distance.

Nevertheless, WSHPs still face difficulties, such as the greatest need for energy during cold spells, seasonal variations in water temperatures, and possible environmental constraints on water abstraction. To address these issues, coupling TES with WSHP systems offers a viable approach. For maximizing the utilization of thermal energy in a water source, Shin et al. [184] proposed a heat source compensation strategy. This enables the WSHP to utilize the TES as a supplementary heat source when the temperature of river water is low. A transient simulation tool was used to assess the performance of the hybrid, hybrid compensation, and compensation-based WSHP under various operating conditions, as shown in Fig. 19. Hybrid SWHP are utilized to offer a continuous heating operation by switching to a boiler when the temperature of the river water falls below a specific threshold limit, as shown in Fig. 19 (a). However, installing a boiler in a hybrid SWHP may result in higher initial cost and energy demand, which may lead to an increase in greenhouse gas emissions. Consequently, the TES was employed as a heat source at low river water temperatures to replace the hybrid system with a compensation SWHP. Fig.19 (b) illustrates that the compensated WSHP operates in two modes: heating mode with a heat source during the day and TES mode for night heating. Even in extremely cold river water, the compensated WSHP could provide continuous heat without requiring additional generators. As TES temperature falls below 21 °C or unable to extract heat from the river at night, the compression mechanical drive is utilized by consuming high electricity for supply heat, which will emit more emissions as compared to the gas boiler. Therefore, at this stage, a hybrid compensation WSHP, as shown in Fig. 19 (c), was considered to be in operation, and would consume less primary

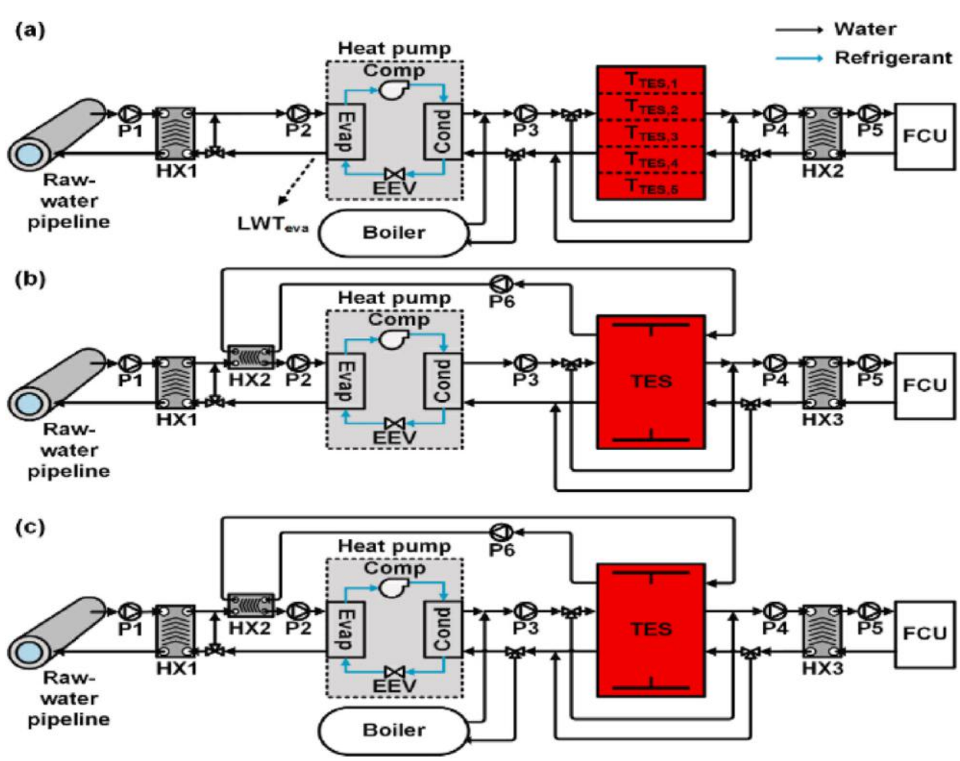

Fig. 19. Different system configurations of WSHP a) Hybrid-WSHP b) Compensation-based WSHP and c) Hybrid compensation-WSHP [184].

energy than the compensated WSHP. The slight change in the condensation and evaporation pressures at night also allowed reasonably high COPs to be obtained. The performance was evaluated by varying the evaporator exit-water temperature, and the late-night heat source compensated for the reference temperature and TES size. The findings showed that compensating WSHP had better performance in terms of energy, environment, and economy compared to conventional heating and cooling. Hybrid compensation was found to have lower carbon emissions, but it exhibited a 19.5 % greater life cycle cost (LCC) than the compensating WSHP.

According to lab and pilot tests, WSHPs using PCM-based TES have COP improvements of 10–25 %. Other advantages include less compressor cycling and better system response to shifting building loads. According to certain research, there has also been a notable decrease in peak power consumption, which supports goals for system flexibility. There are still significant limitations in spite of these encouraging findings. Little information is available from real-world, multi-season field experiments, and the majority of research depends on small-scale prototypes evaluated under controlled conditions. Overall, WSHP coupled with PCM based TES exhibits better performance with stabilizing temperatures, increasing COP, and lowering peak grid loads than the ASHP and conventional systems. The four main important factors, building type (office, schools, and residential that require different heat demands), type of water source, distance to water intake, and TES, should be carefully considered when designing a system because these factors affect the performance, energy, and cost of the system. Immersion heat exchangers, such as helical coil heat exchangers, freeze during operation in extremely cold winter climates, which significantly impairs the ability of the system to transfer heat. Although beach well intake performs better than helical coil water intake, the construction of a beach well necessitates more challenging geological conditions and is not as economically feasible as helical coil water intake. Decarbonization of building heating could be greatly achieved through WSHP systems upgraded with PCM-based TES within the next ten years, if the financial and technical gaps are methodically filled through concerted research and demonstration projects.

3.4. Ground source heat pump (GSHP) with TES

Geothermal energy sources are the readily available energy sources in different places around the globe. Ground-source thermal energy can be utilized in HP as a heat source to minimize fossil fuel consumption. GSHP systems, which include the Earth's energy, geothermal, and geoexchange systems, have recently attracted significant interest as sustainable alternative energy sources for building cooling and heating applications [10]. The GSHP delivers heat energy from the ground during the winter season for heating, whereas in the summer season, heat is extracted from buildings and dumped into the ground or earth through heat exchangers for cooling [9]. ASHPs are the most widely adopted technology for heating applications, owing to their simplicity and ease of installation. However, its performance deteriorates during winter, as the outdoor air temperature decreases significantly. Therefore, GSHPs are preferred over ASHPs because of their stable operating temperatures in cold climates.

GSHP are generally categorized into two groups: open loop (ground water) and closed loop (ground couple) [185], as shown in Fig. 20. An open-loop system consists of three typical designs: extraction well, surface water, heat extraction, and reinjection wells. The most widely used design configuration is the extraction and reinjection well, which is also referred to as a double system. This system requires the use of at least two wells to pump ground water into the first well, transfer heat to and from the circulating fluid, and then discharge water into the second well, as shown in Fig. 20 [186]. However, open-loop systems have certain drawbacks such as water contamination and thermal short circuits, which hinder their applications. The closed-loop system comprises of continuous pipe loops positioned on the ground. The closed-loop type

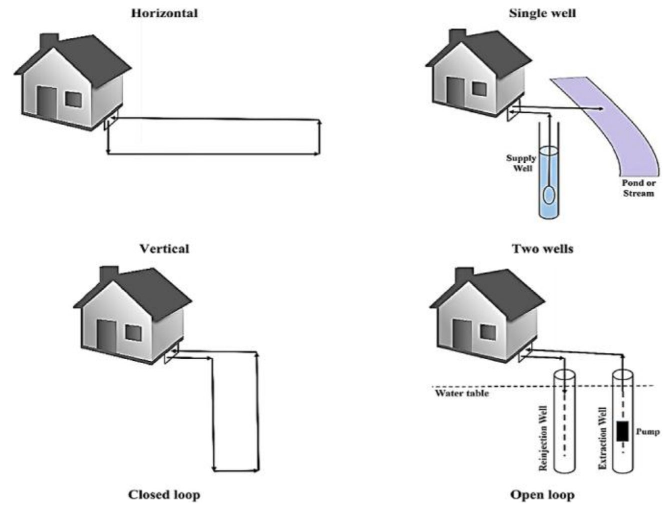

Fig. 20. GSHP with different design configurations [186].

is classified into two categories based on the installation type: vertical borewells and horizontal loops [187]. The land field required for vertical installation is comparatively small because its depth typically ranges from 80 to 500 m. However, specialized equipment is required to install a vertical ground heat exchanger, which increases the initial installation cost. Conversely, simple equipment is required for horizontal heat exchanger installations, which is having a 1–3 m installation depth. This results in an economically feasible advantage over the vertical type [188].

Further, Expensive initial drilling costs, lengthy payback times, and possible ground thermal imbalances brought on by continuous heating without seasonal recharging are additional major obstacles for GSHP systems. A viable solution to these problems is the integration of PCM based TES, which minimizes load on ground heat exchangers and helps maintain balanced ground temperatures and prolong the borehole field's useful life. Lv et al. [189] performed a comparative analysis of GSHP-coupled TES and conventional GSHP. TRNSYS was used to simulate the developed system model, and a project model was fabricated to perform experimental tests. Furthermore, it was shown that, in contrast to standard GSHPS, GSHPS equipped with an TES tank can mitigate temperature fluctuations by shifting load and modifying operation strategy to maintain the HP system in a stable operating condition. According to the results, the integrated system has a greater COP than the conventional system by 0.37 in winter months and 0.04 in the summer. In terms of off-peak power pricing, the integrated system saved 18.3 % and 35.2 % in winter and summer, respectively, compared to the conventional system. It was concluded that the coupled system distributed energy is a more acceptable way, which would save considerable energy and minimize emissions throughout the operation phase by using low-cost power and renewable energy. Thus, there are promising application prospects and market demand for compound energy-supply systems.

Conventional ground heat exchangers (GHEs) involve deep borings equipped with high-density polyethylene pipes that circulate HTF. This deep drilling resulted in an increase in system cost. Thus, to lower costs, researchers have developed a technology by embedding HTF pipes into foundations, which are referred to as energy piles [190]. Energy piles have become increasingly popular globally over the past 20 years. A pile is a long, sturdy cylinder rammed into the ground, usually made of concrete, to provide a stable base for construction built on top of it. Thus, it can fulfill the dual purpose of assisting buildings and acting as a vertical heat exchanger. Thus, it is possible to avoid the additional land use and construction expenses associated with a standard GSHP system with vertical boreholes [191]. The diameter of the energy pile is around 0.5–1.5 m, which is greater than the boreholes having a diameter of

0.1–0.3 m, respectively. The thermal aspect primarily focuses on optimizing the pipe arrangement implanted in the pile body. The primary focus of the thermal aspect was to optimize the design of the pipe embedded in the pile body [192]. A larger diameter of the pipe can be advantageous for improving the heat exchange rate by expanding the area of contact between the pile body and the thermal piping [193]. To enhance the thermal performance of the pile body, a PCM can be included [194]. Akrouch et al. [195] anticipated that an energy pile-based GSHP system would experience a build-up of cold in the ground over time when the heating requirements significantly outweigh the cooling demands. Therefore, a seasonal TES system should be coupled with an energy-pile-based GSHP system to enhance the performance and operating period. To meet the heating and cooling requirements of high-rise residential buildings, Ma et al. [196] developed an energy-pile-based GSHP system coupled with seasonal solar TES, as shown in Fig. 21. To minimize the temperature fluctuations in the energy pile and prevent cold buildup in the ground, an optimized design process was established for the combined system. A numerical study was conducted to assess the system performance under various ground conditions and climates with significant heating demands throughout China.

The findings demonstrated that the system underwent three phases in a typical functioning year: the first stage involved injecting heat into the ground quickly, the second stage involved injecting heat into the ground more slowly or not at all, and the third stage involved extracting heat for space heating. The system could easily meet the heating needs of buildings in the cold zone with a solar collector effectiveness of 40 % and 58 %, respectively. In situations where the area is extremely cold, the ability of the system to meet heating demands depends on favorable ground conditions. Additionally, the system performance may be enhanced by adding a domestic hot water (TES) preheating process, particularly in situations where the ground is unfavorable.

Despite the tremendous potential of geothermal energy, three primary factors prevent geothermal systems from being extensively used: expensive drilling costs, an imbalance of energy on Earth, and an acute lack of drilling areas. To overcome these issues, Shukla et al. [197] developed a novel foundation-based geothermal heat exchanger system using a PCM. By using foundation caisson, combined structural and energy systems are formed in a single ground installation, which lowers the costs of both construction and installation. The expenses associated with the foundation caisson are less than those associated with drilling a borehole for a vertical heat exchanger that functions only to promote heat exchange. The effect of adding PCM to a foundation caisson under heating, cooling, and building load profiles was examined using a numerical model. Experiments showed that the caisson performed better when PCM with higher thermal conductivity was used. Furthermore, PCM contributes to improved thermal performance, as indicated by its lower primary energy consumption.

The incorporation of heat exchangers into screw piles to form energy piles is a rapid and cost-effective option. Despite this, improved methods for managing thermal waves and thermal resistance in energy piles are still necessary. Fei et al. [198] developed a new idea to resolve these issues by incorporating PCM in energy screw piles, as shown in Fig. 22 (a), and investigated it through numerical simulations. Using a typical grout-filled screw pile as a comparison, the results demonstrate that with an appropriate choice of PCM-solid combinations, PCM energy screw piles may lower the fluid temperature in the heat exchanger and the thermal resistance. Cao et al. [199] compared energy piles backfilled with different materials such as PCM, water, and normal grout for HP applications, as shown in Fig. 22 (b), and the results revealed that energy piles with PCM and grout exhibited greater thermal performance than the water back filler. The thermal performance of PCM energy piles was more significantly affected by intermittent operation than that of regular grout-backfilled energy piles. Enhancing the thermophysical characteristics of PCM backfill materials and their intermittent operation are crucial for maximizing the thermal efficiency of the energy pile and obtaining the benefits of PCM backfill materials. Moreover, Table 5 provides an overview of the major experimental and numerical studies

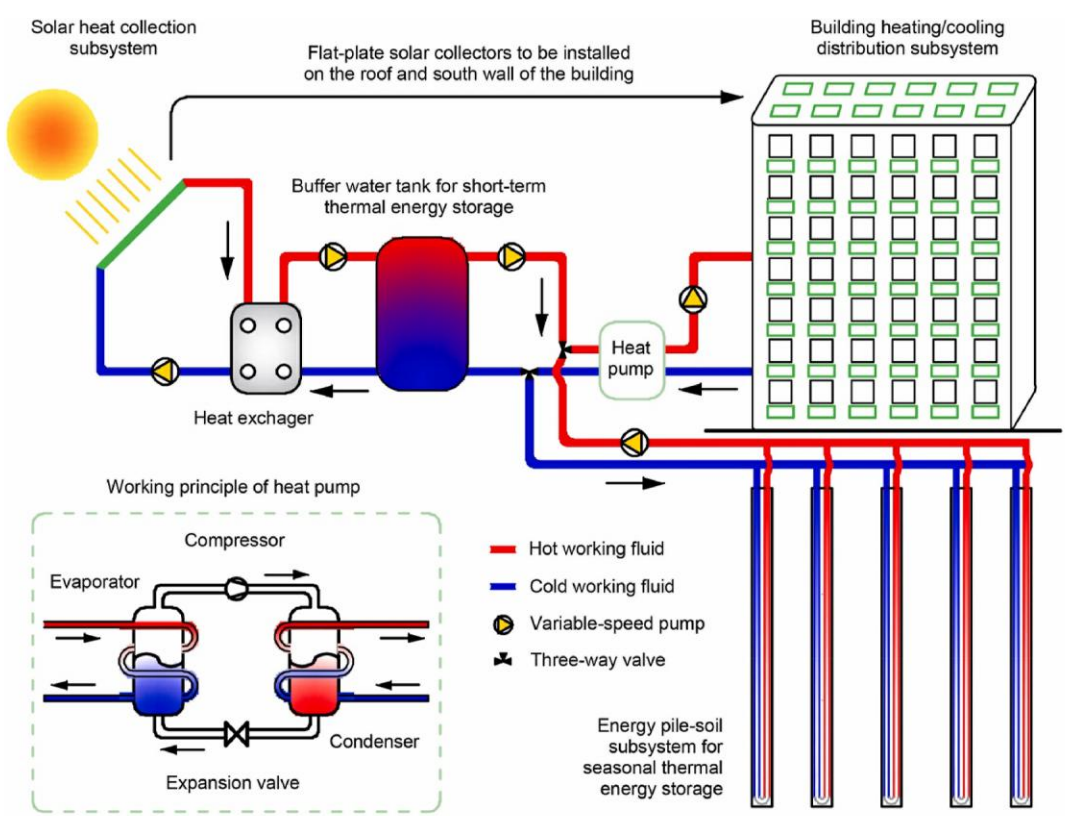

Fig. 21. Schematic representation of the GSHP utilizing energy piles and seasonal TES [196].

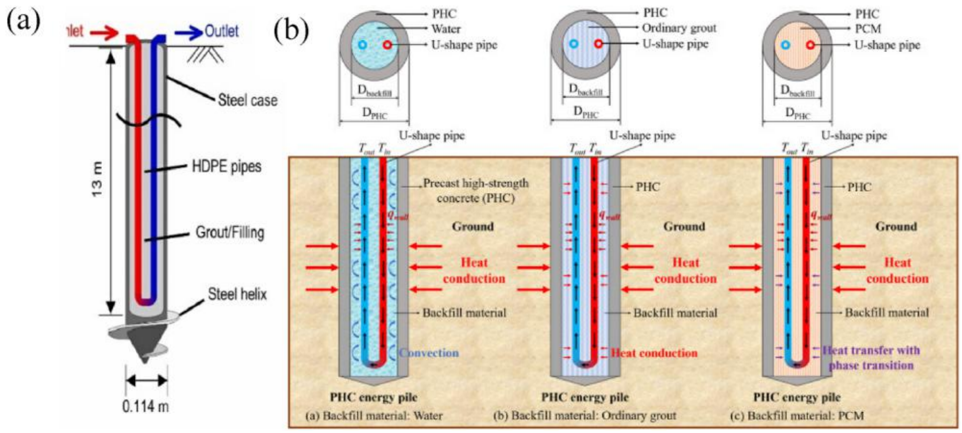

Fig. 22. Schematic of a) Screw energy pile [198] **b) PHC energy pile** [199].

Table 5
An overview of current GSHP technology coupled with PCM-TES

Study/ Reference	System Configuration	Key Findings	Benefits	Limitations/Challenges	Commentary
Lv et al. [189]	GSHP with PCM-based TES	COP increased by 0.37 in the winter and 0.04 in the summer, resulting in 18–35 % cost savings	Utilizes off-peak power, modifies load, and stabilizes HP functioning.	No data on durability across many seasons	potential integrated method, but it requires field testing
Akrouch et al. [195]	Energy pile coupled with seasonal PCM-TES	Possible cold accumulation reduced by seasonal TES	Energy piles operational life is extended	Complex monitoring and seasonal scheduling are necessary.	Operation of sustainable energy piles need seasonal TES.
Shukla et al. [197]	Foundation caisson integrated with PCM	Decreased primary energy use and enhanced thermal efficiency	Reduces installation expenses by combining structural and energy functions.	Long-term tests and strong PCM encapsulation are required.	A innovative hybrid strategy offering significant potential for cost savings
Fei et al. [198]	Screw energy pile integrated with PCM	Reduced fluid temperatures and lowered thermal resistance	Enhanced heat transfer and economical effective construction	Optimizing PCM selection is necessary.	PCM-integrated screw piles show promise approach, but specific material characteristics are needed.
Cao et al. [199]	Energy piles filled with PCM and different backfill	Greater thermal efficiency compared to water/grout fillers	Increased energy efficiency while operating intermittently also.	PCM behavior that is susceptible to control and cycling	PCM backfills' promise is highlighted, however improved operation techniques are required.

investigating energy piles, foundation-based heat exchangers, on GSHP systems couple with PCM -TES.

Based on the studies, it was found that GSHP technology development has been evolved in recent years to establish systems that are more cost-effective and efficient in improving system performance under different environmental operating conditions. Furthermore, there has been increased interest in combining GSHPs with additional sources of renewable energy, such as solar and wind, to build hybrid systems that can deliver energy-efficient heating and cooling without negatively affecting the environment. The development of novel materials and designs to enhance the effectiveness of heat transfer has been the focus of recent developments in GSHPs. Numerous technical difficulties, such as those related to design, installation, size, optimization, maintenance, and integration, confront GSHP systems. One of the most important technical problems with GSHP systems is the design and installation of the ground loop, which transfers heat to and from Earth. This can be a challenging and costly procedure, particularly if the soil is unsuitable for installing a ground loop or if it is impossible to reach the ground. Moreover, it can be challenging to appropriately size GSHP systems, because the system size must match the heating and cooling requirements of the building. Poor performance and increased energy costs can result from improper sized systems. Optimizing GSHPs may be a challenging task because of the impact of several factors on the system performance, such as ground temperature, ground loop geometry and design, and heat exchange efficiency. A viable strategy for improving thermal performance and thermal storage capacity is the integration of a PCM-based TES with a GSHP system. PCMs can reduce thermal interference and substantially decrease temperature fluctuations within borehole heat exchangers, which can improve system performance and potentially save energy. Therefore, the incorporation of PCM into GSHP heat exchangers has a significant effect on the energy savings and performance of the system. Overall, PCM coupled GSHP systems have the potential to become a key component of reliable, low-carbon heating and cooling systems for both residential and commercial buildings by reducing ground temperature drift and promoting steady, sustainable operation over many years, if the above discussed issues are methodically resolved.

3.5. Waste heat recovery heat pump (WHSHP) with TES

Combustion, heating, and cooling are the industrial processes that release waste heat into the atmosphere. The temperature of waste heat varies among industrial operations, ranging from 25 °C to 400 °C [200]. Thus, the waste heat was categorized as high-, medium-, or low-grade. Furthermore, the food and beverage processing industry accounts for 25 % of the generation of industrial waste heat [201] and has the potential to be a major source of energy efficiency for industries. Heat from low-grade renewable waste or industries cannot be utilized directly; however, it may be reclaimed by upgrading it to the necessary high grade through HPs. Currently, thermal energy conversion, thermal storage, and HP are the technologies used for waste heat recovery. HP have emerged as a mature technology for waste heat recovery owing to their effective energy-saving and reduced emission capabilities with practical significance [202].

A significant amount of heat is generated by electric devices in a data center (DC), and the cooling system for these devices uses approximately

40 % of the DC's overall energy [203]. Numerous studies have been conducted on DCs to enhance the cooling system performance and utilize waste heat. The issue of adding extra equipment to the traditional DC waste-heat recovery system can be resolved by proposing an efficient waste-heat recovery HP system that uses waste heat from DCs [204]. Jang et al. [205] developed an innovative WHSHP to lower energy usage for heating residential areas and cooling DCs. Water with a temperature below 12C was used to cool the DC, and the waste heat from the DC was recovered through the WSHP for residential heating applications, as shown in Fig. 23. Utilizing cold-temperature water to cool the DC reduces the chance of water freezing in the WSHP evaporator. In addition, by using DC waste heat, the WSHP performance may be enhanced, resulting in the best performance in mid-winter.

Wang et al. [206] investigated the performance of a GSHP coupled with a low-temperature industrial waste heat source ground heat exchanger. The system comprises three components: waste heat collection and exchange, a ground soil heat exchanger for heat injection and extraction, and a GSHP attached to buildings for heating applications, as shown in Fig. 24 (a). The performance of the system was significantly affected by the arrangement of the vertical boreholes for heat injection and extraction. As shown in Fig. 24 (b), the borehole cluster is separated into inner and outer sections. The GHEs attached to the HP are indicated by the inner hollow circles, whereas the GHEs connected to industrial waste heat are indicated by the outside solid circles. Depending on the real demands, the system can be configured as a square or circular. The main purposes of this system design are soil thermal energy storage and waste heat recovery based on the heating and cooling needs of the area. This demonstrates that adding low-temperature waste heat to soil can facilitate waste heat recovery and soil thermal imbalance, offering substantial assistance in areas that require heating, particularly in cold climates.

Ma et al. [207] developed a novel method for combining a PCM-based heat storage device with a sewage waste-source HP. A method that uses the thermal energy found in wastewater to collect and reuse energy is called sewage source HP (SSHP). According to several studies, it has been extensively used for heating buildings and has significant potential for lowering energy use and mitigating carbon emissions. Sewage heat sources alone cannot provide maximum energy efficiency for an SSHP system. The integration of renewable energy sources may help mitigate the present energy crisis by optimizing energy efficiency and reducing energy consumption. Moreover, additional storage devices can address the instability problem because solar energy depends on the time and weather. To reduce energy consumption and improve the heating time, researchers have suggested a PCM heat storage device in conjunction with an SSHP. The heat harnessed from the solar and some portion of the heat from the SSHP were collected and transferred into PCM storage, as shown in Fig. 25, to allow the peak heating load regulations in building applications. These findings imply that adding a phase change to the heat storage unit significantly increases energy efficiency and economic feasibility.

From these discussions, it is evident that waste heat from data centers, sewage, and industries can be used as a heat source for WSHP for residential or industrial heating applications. WHSHP offers better performance with minimal emissions than ASHP and WSHP, where waste heat is abundant. According to studies, PCM-TES coupled WHSHP systems can increase COP by 10 %–30 %, depending on the waste thermal stream's and the PCMs characteristics. PCM-TES can assist in maintaining continuous high COP operation in WHSHPs while regulating temperature variations in waste heat fluxes, such as those caused by fluctuating wastewater temperatures. Furthermore, the integration of PCM storage and renewable sources into WHSHP allows the storage of heat from waste heat sources that are not utilized. This leads to a reduction in energy losses, improves efficiency and operating time, and reduces energy consumption and emissions. The applications of WSHP are limited to specific areas, such as industries and data centers, owing to the availability of waste heat. Therefore, WSHP are not suitable for independent or standalone applications and are only suitable for mostly industrial and non-residential areas. Implementing control strategies with an efficient TES design can maximize energy utilization and performance. In order to balance cost and thermal density, hybrid TES designs have been developed; moreover, advanced control systems that coordinate TES charge/discharge with industrial process waste heat profiles are showing promise.

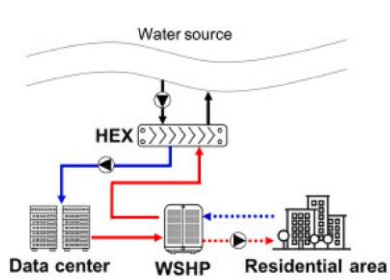

Fig. 23. Schematic of DCs waste heat recovery with WSHP [205].

4. Emerging technologies of PCM-based TES coupled with HP for enhancing performance

Although it was established from an aforementioned discussion that PCM-based TES in conjunction with HPs significantly improved performance, the traditional PCMs' low thermal conductivity, phase segregation, subcooling, and poor long-term cycle durability remain technical problems. Novel PCM-based TES technologies are presently being investigated as a solution to these problems. With the implementation of these technologies, the PCM-based TES may be able to integrate next-generation HP, which might enhance its techno-economic viability, environmental sustainability, efficiency, and flexibility of operation.

4.1. Nano-enhanced PCMs

Organic PCMs exhibits low thermal conductivity (usually between 0.2 and 0.4 W/mK), which limits the rate of heat transfer during the melting and solidification process that leads to poor dynamic responsiveness and prolonged charging and discharging periods. To solve this, a high-conductivity nanomaterials like graphene, carbon nanotubes, metal nanoparticles (Cu, Al, Ag), or metal oxides (AlO_3, TiO_2) are included to form as a nano-enhanced PCMs [208]. These nanoparticles maintain latent heat capacity by establishing conductive paths inside the PCM matrix, increasing effective thermal conductivity by up to five times and resulting in an improved performance of PCM based TES systems [209,210]. Moreover, dual nanoparticle hybrid nanocomposites can take advantage of synergistic effects to further enhance heat transmission. Nonetheless, homogeneous dispersion, stability, and agglomeration reduction of nanoparticles continue to be major research problems [211].

4.2. Shape stabilized and composite PCMs

Shape stabilization is technology to implant PCM inside a porous or polymer support matrix (such as expanded graphite and polyurethane foams) to form as shape stabilized PCM composite [212]. These composite PCMs exhibit superior form stability, high encapsulation ratio with negligible leakages as compared to the solid-liquid phase transition PCMs. Specifically, expanded graphite shape stabilized PCM offers significant increase in thermal conductivity (up to 1–2 W/mK) without effecting the latent heat capacity [212]. In addition, embedding silica-based supports or aerogels improves the mechanical and thermal stability even further. Therefore, shape stabilized PCM composite will be the best suitable PCM based TES for HP applications to enhance

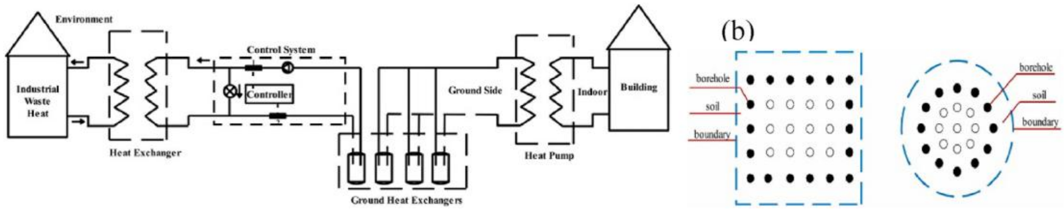

Fig. 24. Schematic of a) Industrial waste heat recovery and storage coupled with GSHP and b) configurations on borehole arrangement [206].

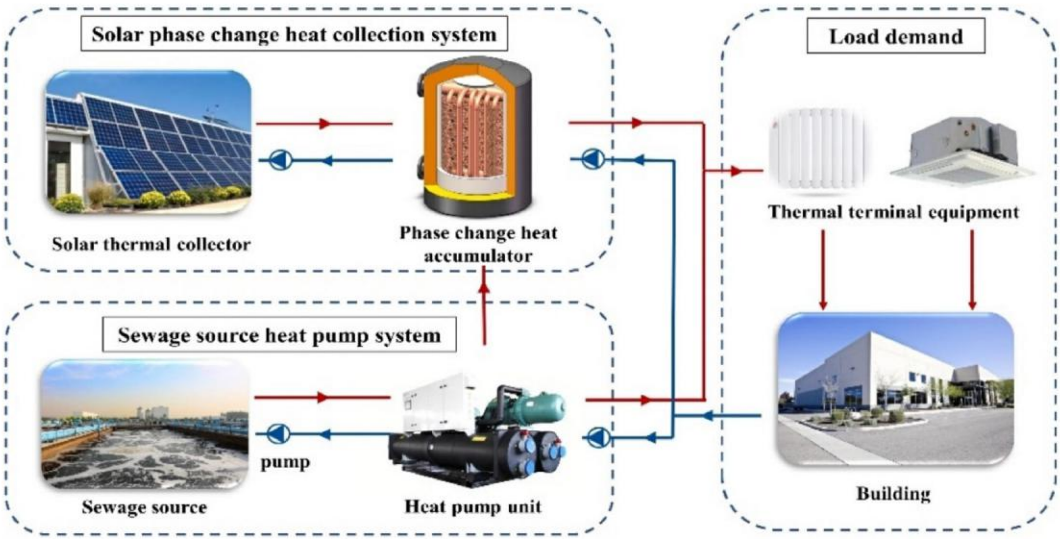

Fig. 25. Schematic of SSHP coupled with solar PCM based TES system [207].

performance [213,214].

4.3. Advanced PCM encapsulation

Encapsulation is the process of enclosing or embedding PCM in a matrix or protective shell. Micro and nano encapsulation of PCMs emerged to be advanced technology to enhance heat transfer, cycle stability and chemical compatibility [215]. PCM cores are encased by using polymers, silica and metal shells to produce micro-encapsulated PCMs (typical diameter 1–100 μm), which eliminate leakage, improved dispersion and arguments transfer in the PCMs [216]. Direct incorporation of PCM microcapsules into heat exchanger fluids might result in a phase change slurry (PCSs) with decreased subcooling and improved convective heat transfer in the systems. Similarly, nano-encapsulation method attains grater surface area to volume ratio, that allows faster rate of temperature response and enhanced stability [217]. These emerging encapsulation techniques offer increased energy storage performance, enhanced safety, and more flexibility for a wide variety of thermal applications like HPs integration [218,219].

4.4. Bio-based PCMs

In the past years, bio-based PCMs have gained significant attention and better substitutes for inorganic or petroleum-based PCMs. These materials are biodegradable, low toxicity, low flammability and have a lower carbon footprint, because they are made from natural and renewable resources including fatty acids, plant oils, and their derivatives [220]. For instance, fatty acid-based PCMs, such as lauric acid and capric acid have demonstrated a better TES capacity, moderate phase transitions temperature and stable cyclic performance [221]. To adjust their melting points and increase their thermal durability, recent research has also looked at eutectic combines of bio-based materials [222,223]. Hence, bio-based PCMs offer a viable, sustainable option for TESs, aiding in the decarbonization of the building heating applications through HP integration [224].

4.5. 3D printed PCM based TES

PCMs-incorporating 3D-printed TES devices have been made possible by recent developments in additive manufacturing [225]. The interior design, porosity, and geometries of TES devices can be precisely controlled by three-dimensional (3D) printing and all these together leads to maximize heat transmission, reduce thermal resistance, and increase system compactness [226]. Through the incorporation of PCMs into intricate 3D-printed structures or lattices, heat flow paths may be customized and PCM encapsulation optimized, resulting in decreased leakage and improved cycle stability. In order to further improve thermal conductivity and heat transfer performance, 3D printing also makes it possible to include high-conductivity additives into PCM composites. Additionally, this technique has made it possible to develop hybrid structures that combine latent and sensible heat storage, resulting in greater design flexibility and effective performance [227].

Summarizes that, the integration of cutting-edge PCM-based TES technologies with HP has great potential to enhance system efficiency, operational flexibility, compactness and sustainability. Conventional PCM drawbacks including leakage, low heat transfer rates, and poor cycle durability have been overcome by recent advances such shape-stabilized PCM composites with strong structural stability and minimize leakage, nano-enhanced PCMs and advanced encapsulating methods show excellent thermal conductivity resulting in greater heat transfer. Furthermore, bio-based PCMs promote decarbonization goals by providing renewable, biodegradable, and ecologically harmless substitutes over traditional PCMs. Additionally, the development of additive manufacturing techniques has increased the design options and operational performance of PCM-based TES systems by enabling 3D-printed systems with customized geometries and hybrid heat storage capabilities. Therefore, these emerging developments offer a significant step toward the development of next-generation PCM-based TES technologies that can be easily incorporated into heat HPs for effective thermal energy management and to improve efficiency of the systems.

5. Energy, economic and environment

Any system should be cost effective and exhibit good performance. From an environmental perspective, it is important factor for us to reduce pollution caused by HP systems. The reduction of CO_2 emissions and energy consumption is gaining the attention of researchers and the public worldwide, particularly when combined with solar thermal systems. In this regard, estimating the environmental benefits of the systems and evaluating their energy and economic viabilities are critical. This section provides a brief discussion of numerous studies describing the energy, environmental, and economic performance of systems.

Yu et al. [228] conducted an economic study on an ASHP with latent TES for space heating in China. A mathematical model was developed to assess the viability of the proposed system from environmental and economic perspectives. The proposed ASHP systems coupled with PCM TES were compared with two-stage ASHP, coal-fired boilers, gas boilers, and direct electric heating systems in China. According to the results, the gas boiler and HP systems exhibit better performance from an energy perspective, whereas electric heating (DEH) and coal-fired boiler (CFB) are not advised for space heating in any location because of their higher primary energy consumption (PEC) values, as shown in Fig. 26 (a). In conclusion, the DEH is not recommended for space heating because of its high energy consumption, CO_2 emissions, and operating costs, although it has the lowest investment cost, as shown in Fig. 26. In addition, CFB are not appropriate for heating applications because of their high primary energy consumption. WGB perform well economically, environmentally, and in terms of energy conservation. However, the widespread use of WGB has been constrained by China's unequal distribution and restricted natural gas output.

Furthermore, owing to the low power generation efficiency, it is evident that the CO_2 emissions of the HP systems are approximately twice those of the CFB, as shown in Fig. 26 (b). However, emissions are transferred from residential areas to power plants through the adoption of HP systems. Furthermore, energy sources may be upgraded and retrofitted from fossil fuel energy to renewable energy, further reducing CO_2 emissions from HP systems. The ASHP-LTES is more cost-effective, environmentally friendly, and energy-efficient than the QTASHP for extremely cold regions. The additional TES unit in an ASHP initially makes it more expensive than a two-stage ASHP, as shown in Fig. 26 (c). Furthermore, one of the main factors limiting the widespread use of HP systems is their higher initial cost compared to traditional heating systems. However, owing to recent industrial developments and rising market demand, the initial cost of HP systems is expected to decrease steadily. Additionally, setting the discount percentage of the TES unit at 40 % reduces the payback period of the ASHP compared with the two-stage ASHP by approximately six years, suggesting that ASHP coupled with TES is a superior option in extremely cold regions in China. In conclusion, ASHP coupled with LTES are a better choice than other systems in the long term.

Qu et al. [229] performed a comprehensive study on a PVT-WSHP and compared it with a PV ASHP using the TRYNSIS model and experiments. According to the results, a higher monthly energy conversion efficiency was observed in PVT, with an average of 12.35 %, compared with the single PV system, with an average of 9.86 %. Owing to the cooling effect of the PVT panels, the electrical conversion efficiency of the PVT-WSHP heating system improved by 25.3 %, respectively. The PVT-WSHP heating system consumed 1681.01 MJ of energy annually, whereas the single ASHP water heater system utilized 1614.56 MJ. This marginal difference was due to the higher energy consumption of the water pump. Compared with the PV-ASHP system, the annual cost of the PVT-WSHP system was lowered by 217.7 yuan and had a payback period

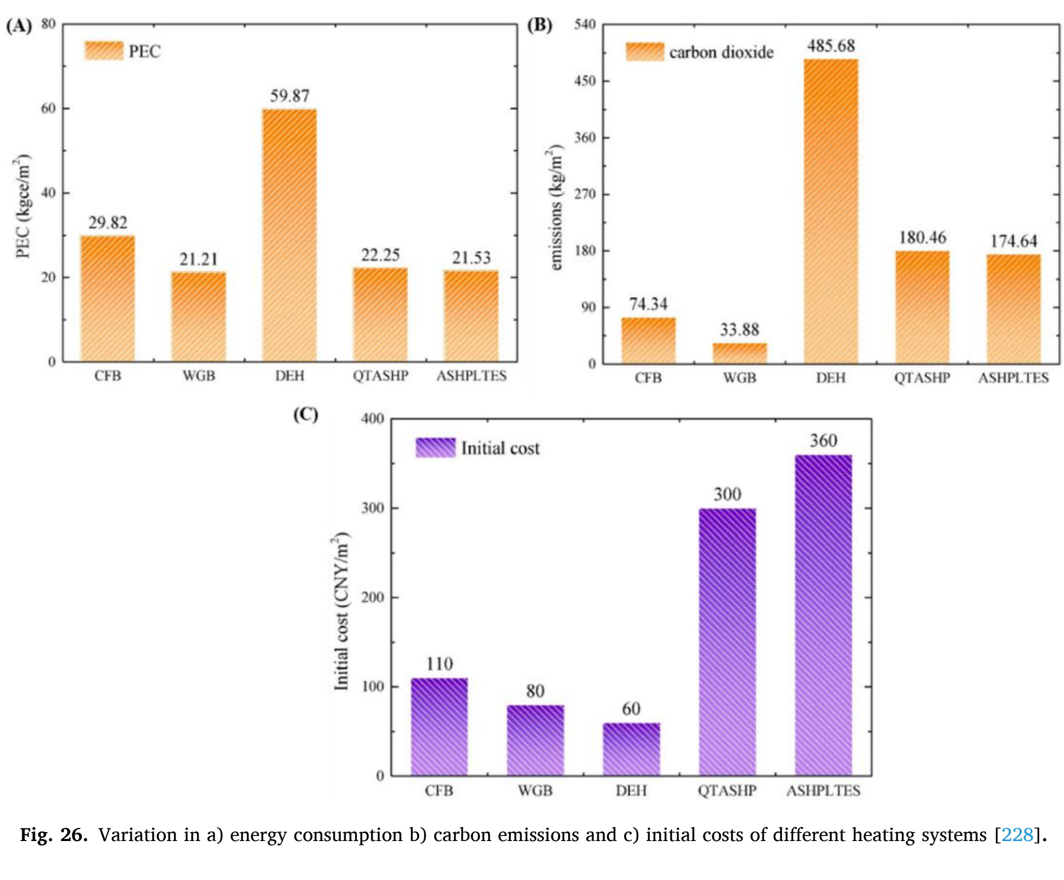

Fig. 26. Variation in a) energy consumption b) carbon emissions and c) initial costs of different heating systems [228].

of six years. The advantages of environmental preservation were evident in both systems. In contrast to the PV-ASHP system, the PVT-WSHP heating system delivered more heat and electricity, resulting in greater emission reductions and standard coal savings.

Pochwała et al. [230] evaluated the viability of utilizing air-to-water HP based on renewable energy sources to avoid building degradation, preserve their historic significance, and ensure that they are compatible with current sustainable energy and decarbonization standards. This study compares two different HP systems: 1) an air-to-water HP that runs on electricity and ii) a gas absorption HP. Currently, the building has a 550-kW fixed-temperature boiler that runs on coal. These findings led to the conclusion that gas-powered air HP are a more advantageous option for buildings. The simple payback period was four years in the gas scenario and five years in the electricity-based scenario. Compared to coal-fired boilers, electricity-based HP decrease heating expenses by more than 72 % (from 0.222 EUR to 0.062 EUR/kWh), whereas gas-based HPs decrease heating expenses by 59 % (from 0.091 EUR/kWh), as shown in Fig. 27. Using these technologies, 123.4 tons of CO_2 released into the environment are reduced each year, leading to environmental sustainability. Based on the study, it can be said that electric based HPs are a more reasonable option since they have significantly lower operating expenses and are marginally expensive than gas absorption HPs.

Maddah et al. [231] performed a comparative study on three different HP technologies, namely industrial waste-WSHPs, ASHP, and GSHP, in terms of energy, economy, and environment. Fig. 28 (a) depicts the COP and work energy consumption for different HPs based on a 50-kW heat capacity. The ASHP system exhibited a lower COP than the other systems owing to the lower heat capacity of air, which implies that more energy is consumed to deliver the same output as the other systems. Additionally, the GSHP system consumes more energy than the WSHP, which results in poor performance, as shown in Fig. 28 (b), demonstrating that using the waste-WSHP system rather than the ASHP cycle lowers the CO_2 emissions and power consumption by 42.229 tons and 71.941 MWh, respectively. This leads to savings in costs of 8028$ during a 6-month operation period. Additionally, the comparison of the waste-WSHP and GSHP system demonstrates that, during a 6-month running period, the WSHP saves 26,698 MWh and decreases CO_2 by 15,671 tons, eventually resulting in 3046$ cost savings as shown in Fig. 28 (b). Therefore, it is evident that the WSHP showed significant benefits over the other systems, and the ASHP was inefficient. The findings indicated that approximately 41 GWh of heat was recovered annually from Iranian casting plants. With a COP of 5.104 under the operating conditions, the WSHP can generate 11.8 MW of thermal energy annually, which is utilized in air conditioning.

Fig. 29 (a) and (b) show the results of an economic study of a PV-assisted HP used for water-heating applications [119,232]. The assessment presented the benefits of the PV-HP over a system without PV and a boiler by considering the system lifetime cost. According to the analysis, the overall cost of the PV-HP system during a 25-year period was 337 €/year, based on an electric cost of 0.15 €/kWh, and approximately 79 % of the energy was saved compared with the boiler and without the PV system. Furthermore, compared to a traditional boiler and a grid-based HP, CO_2 emissions of PV-HP decreased by 82 % according to the environmental study. A PV-based HP incurs higher initial investment cost. However, during operation, it offers significant energy, pollution, and cost reductions.

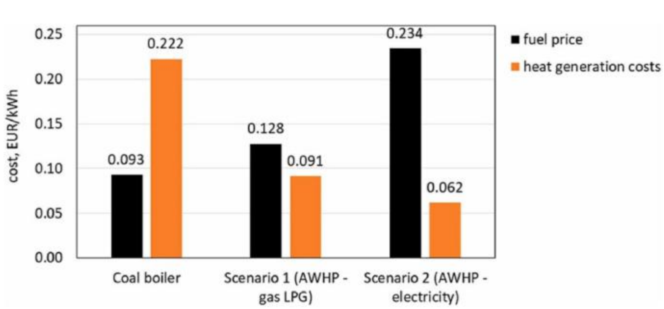

Fig. 27. Comparison of fuel price and heat generation cost for different heating systems [230].

Biglarian et al. [233] conducted a comparative study by considering solar-assisted GSHP, GSHP, ASHP, and natural gas heating systems (NGSH) in terms of energy, economy, and environment. The findings show that the NGSH system has the lowest investment cost, whereas the SA-GSHP and GSHP systems were found to have higher costs, as shown in Fig. 30 (a). The lowest LCC was found in the NGSH, followed by the SAGSHP, GSHP, and ASHP systems, respectively, over a period of 20 years. Consequently, the most cost-effective system may be NGSH. In terms of LCC, the SA-GSHP was also more appealing than the GSHP and ASHP, as shown in Fig. 30 (b). Further, SA-GSHP provides discounted paybacks of 8.6 and 12.1 years, respectively, then that of the GSHP and ASHP. By offering a 30 % incentive for the initial cost of the system, it was discovered that the GSHP and SA-GSHP systems were more cost-effective than the ASHP and NGSH systems. Furthermore, the SA-GSHP emits the least amount of carbon dioxide and is reduced by 9, 36, and 33 %, respectively, compared to those of the GSHP, ASHP, and NGSH systems, as shown in Fig. 30 (c), primarily because the SA-GSHP is more efficient and has the potential to emit minimal emissions powered by electricity obtained through renewable sources.

The coupling of TES with HP systems has significant benefits in terms of environment, energy savings, and economics. Lowering the energy consumption and CO_2 emissions in HP systems is essential from an environmental perspective, and incorporating TES and solar thermal systems may further improve sustainability. In terms of economics, HP systems are an attractive choice, particularly when combined with TES, despite having higher initial expenses than traditional heating techniques. This is due to their high efficiency and long-term operational savings. In terms of energy savings and lowering emissions, studies have demonstrated that gas boilers and HP systems perform better than direct DEH and CFB, respectively. Combining HP with TES and solar thermal systems results in a more effective solution for severely cold climates in terms of operational energy savings and reduced emissions. Long-term heating solutions in severely cold climates. Offering financial aid or incentives for solar thermal and TES systems may lower their initial costs and support their widespread adoption and commercialization.

Finally, a holistic comparison of various HP technologies with and without PCM-based TES has been provided in Table 6. It summarizes the performance, key benefits and challenges. There are numerous benefits of integrating PCM-TES, such as enhanced seasonal performance, less compressor cycling, peak-load shifting, reduced fluctuations in operation, and increased use of renewable energy. The table also identifies significant obstacles that must be methodically overcome through focused research and field tests in order to facilitate successful large-scale commercial deployment, including PCM durability, limited thermal conductivity, and the requirement for sophisticated, predictive control strategies.

6. Conclusions

This review presents a comprehensive analysis of HP systems integrated with PCM-TES for sustainable building heating applications. The integration of PCM-TES has been shown to address several limitations inherent in conventional HP systems, including defrosting inefficiencies, unstable heat supply from renewable sources, and mismatches between energy supply and demand. Based on the reviewed studies, a significant improvement has been observed with the integration of HP into the PCM-TESs. PCM-based defrosting methods have cut defrosting periods by up to 75 % and decreased compressor power usage by 55.8 %, while evaporator-side PCM storage has increased COP by 6.1 %–14 %, depending on the climate conditions. Compared to conventional gas

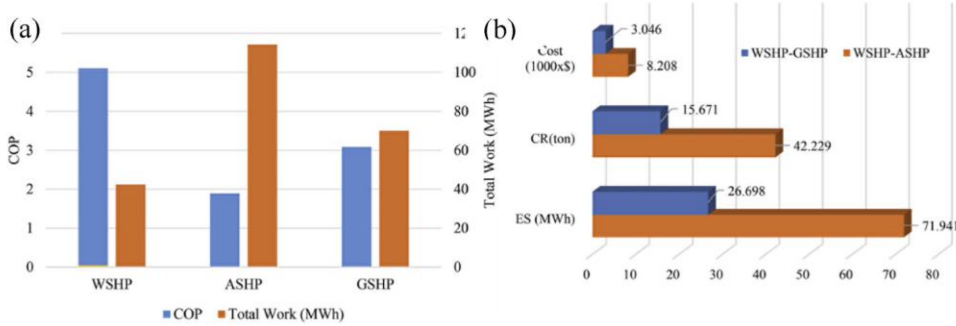

Fig. 28. Comparison of a) COP and work b) Energy savings, carbon emission reduction and cost savings under different HP technologies [231].

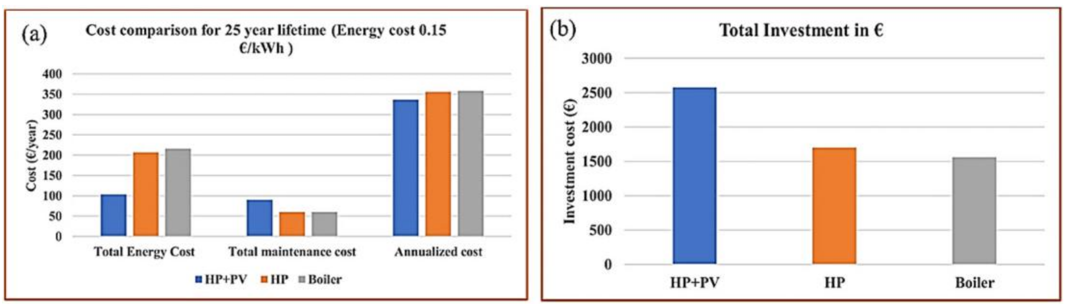

Fig. 29. Comparison of a) various costs accounted for in the operations of systems and b) total investment cost [119,232].

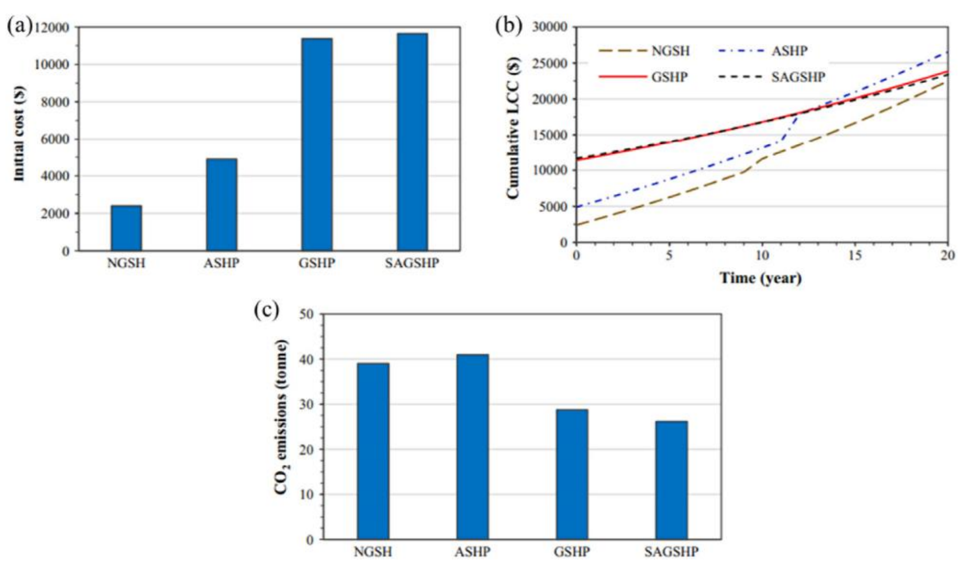

Fig. 30. Comparison of a) initial cost b) LCC, and c) carbon emissions of different heating technologies [233].

boiler systems, dual-source and PVT-assisted HP systems coupled with PCM-based TES showed maximum COP values up to 4.67 and seasonal performance factors exceeding 2.3. In addition, these systems also showed reduced energy consumption of up to 56 % and operating costs of 27.7 %, respectively. The HP integrated with TES having phase change slurry HTF was found to have a COP of 4.7, 43.6 % improvement as compared to the water as HTF. Therefore, it was concluded that with the enhanced thermal load management and improved operating stability, PCM-TES systems can significantly increase the seasonal performance factor and overall energy efficiency of HPs while reducing peak electricity consumption and associated emissions.

Among the various configurations, dual-source and PVT-assisted HPs coupled with a PCM-based TES demonstrated the highest potential for performance improvement and energy flexibility. Key considerations, such as appropriate PCM selection based on the phase-change temperature, TES placement (evaporator or condenser side), and thermal conductivity enhancement methods, were found to play critical roles in system optimization. In particular, phase-change slurries have emerged as a promising hybrid solution acting as both a heat transfer fluid and a thermal storage medium, although further investigation is required to address issues such as high pumping power.

Despite these advances, the high initial cost of HP-TES systems remains a major barrier to their widespread adoption. However, studies suggest that targeted government incentives and cost reductions in TES components, especially PCM materials, can significantly improve economic feasibility, with payback periods potentially reduced to less than

Table 6
Comparison of various HP technologies with and without PCM-based TES coupling.

Heat Pump Type	Without PCM-TES	With PCM-TES	Benefits of PCM-TES	Remaining Challenges
ASHP	COP 2.5–3.0 frosting risk in cold climates	COP 3.0–4.0; more effective defrost; less compressor cycles	Better COP, peak-load shifting, and smoother functioning	Cost, long-term durability, and poor PCM thermal conductivity
SAHP	COP 2.8–3.5; solar-energy dependent	COP 3.5–4.5; higher solar energy utilization, consistent energy supply	Improved seasonal solar usage and minimizing solar energy fluctuation.	Limited field demonstrations, complicated controls, and PCM stability in conditions of sunlight
WSHP	COP 3.0–4.0; temperature of water fluctuations during seasonal	COP 3.5–4.5; decreased cycling of the compressor	Minimizes peak loads and maintains stable source temperature	Reliability of encapsulation, fouling, and PCM compatibility with water
GSHP	SCOP 3.5–4.5; ground temperature imbalance issues	SCOP 4.0–4.8; enhanced stability of ground temperature	Balanced seasons variations and longer borehole life	Cost, complex system coupling and PCM integration.
WHSHP	COP 2.8–3.8; waste heat temperature variable	COP 3.5–4.5; Increased usage of waste heat	Enhance energy usage by matching demand for intermittent waste heat.	Different contaminants, fouling, and the lack of reliable field testing

six years in cold climate regions.

In summary, PCM-integrated TES offers a viable pathway for improving the performance, reliability, and sustainability of heat-pump systems in buildings. This study provides a holistic foundation for future research and development and contributes valuable insights for engineers, policymakers, and researchers aiming to advance the commercialization of high-efficiency, low-emission heating technologies.

6.1. Future research directions

- The PCM selection optimization
  Develop standardized guidelines for selecting PCMs with suitable phase-change temperatures based on HP operating conditions, end-user requirements, and climatic zones.
- Phase-change slurry development
  Investigates low-viscosity phase-change slurries with high thermal storage capacity and low pumping power for use as dual-function heat transfer and storage media.
- Thermal conductivity enhancement Explores advanced PCM enhancement techniques, such as metal foams, encapsulation, and nano additives, to improve heat transfer rates and reduce charging/discharging times.
- Hybrid TES systems Design and validate combined sensible–latent TES configurations to maximize the energy density and maintain stable outlet temperatures under varying load conditions.
- Control strategies for TES-HP systems
  Develop intelligent control algorithms for real-time load shifting, peak shaving, and TES utilization optimization in integrated HP-TES systems.
- Application-specific research (e.g., waste heat source heat pumps (WHSHP) Expand studies on under-researched HP configurations, such as WHSHP integrated with TES in industrial and data center settings.
- Techno-economic and environmental evaluations
  Involve region-specific life cycle costs, carbon reduction, and policy impact analyses to guide TES-integrated HP deployment strategies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study was supported by the Mechanical Equipment Technology Development Program of the Korea Evaluation Institute of Industrial Technology (KEIT) funded by the Ministry of Trade, Industry & Energy (MOTIE, Korea) (Grant No. RS-2024-00442911) and the Main Research Program (E0232100-01) of the Korea Food Research Institute (KFRI) funded by the Ministry of Science and ICT.

Data availability

Data will be made available on request.

References

[1] Wang C, Ma M, Su Y, Wang Y, Wang Y, Chen Y, Fan L, Peng C, Deng J. Research on the operation features and optimization methods of heat pumps coupled with mid-deep borehole heat exchangers: on-site measurements and comparative study. Energy Build 2025;328. https://doi.org/10.1016/j.enbuild.2024.115239.
[2] Namdar H, di Schio ER, Semprini G, Valdiserri P. Photovoltaic-thermal solar-assisted heat pump systems for building applications: a technical review on direct expansion systems. Energy Build 2025:115516. https://doi.org/10.1016/j.enbuild.2025.115516.
[3] Hu Z, Li W, Yang C, Huang H, Guo Y, Ge F, Zhang Y. Thermal performance of an active casing pipe macro-encapsulated PCM wall for space cooling and heating of residential building in hot summer and cold winter region in China. Constr Build Mater 2024;422. https://doi.org/10.1016/j.conbuildmat.2024.135831.
[4] Ohene E, Chan APC, Darko A. Review of global research advances towards net-zero emissions buildings. Energy Build 2022;266. https://doi.org/10.1016/j.enbuild.2022.112142.
[5] Wang Z, Luther M, Horan P, Matthews J, Liu C. Residential space heating electrification through a PV-driven hot water heat pump. Energy Build 2025;330. https://doi.org/10.1016/j.enbuild.2025.115319.
[6] Marinelli S, Lolli F, Gamberini R, Rimini B. Life cycle thinking (LCT) applied to residential heat pump systems: a critical review. Energy Build 2019;185:210–23. https://doi.org/10.1016/j.enbuild.2018.12.035.
[7] Akbarzadeh S, Sefidgar Z, Sadegh Valipour M, Elmegaard B, Arabkoohsar A. A comprehensive review of research and applied studies on bifunctional heat pumps supplying heating and cooling. Appl Therm Eng 2024;257. https://doi.org/10.1016/j.applthermaleng.2024.124280.
[8] Demierre J, Favrat D, Schiffmann J, Wegele J. Experimental investigation of a thermally driven heat pump based on a double Organic Rankine Cycle and an oil-free compressor-Turbine Unit. Int J Refrig 2014;44:91–100. https://doi.org/10.1016/j.ijrefrig.2014.04.024.
[9] Mustafa Omer A. Ground-source heat pumps systems and applications. Renew Sustain Energy Rev 2008;12:344–71. https://doi.org/10.1016/j.rser.2006.10.003.
[10] Sarbu I, Sebarchievici C. General review of ground-source heat pump systems for heating and cooling of buildings. Energy Build 2014;70:441–54. https://doi.org/10.1016/j.enbuild.2013.11.068.
[11] Wang Z, Luther MB, Amirkhani M, Liu C, Horan P. State of the art on heat pumps for residential buildings. Buildings 2021;11. https://doi.org/10.3390/buildings11080350.
[12] Gaur AS, Fitiwi DZ, Curtis J. Heat pumps and our low-carbon future: a comprehensive review. Energy Res Soc Sci 2021;71. https://doi.org/10.1016/j.erss.2020.101764.
[13] Fischer D, Madani H. On heat pumps in smart grids: a review. Renew Sustain Energy Rev 2017;70:342–57. https://doi.org/10.1016/j.rser.2016.11.182.
[14] Valancius R, Singh RM, Jurelionis A, Vaiciunas J. A review of heat pump systems and applications in cold climates: evidence from Lithuania. Energies 2019;12. https://doi.org/10.3390/en12224331.
[15] Sadjjadi BS, Gerdes JN, Sauer A. Energy flexible heat pumps in industrial energy systems: a review. Energy Rep 2023;9:386–94. https://doi.org/10.1016/j.egyr.2022.12.110.
[16] Lämmle M, Metz J, Kropp M, Wapler J, Oltersdorf T, Günther D, Herkel S, Bongs C. Heat pump systems in existing multifamily buildings: a meta-analysis of

field measurement data focusing on the relationship of temperature and performance of heat pump systems. Energy Technol 2023;11. https://doi.org/10.1002/ente.202300379.
[17] Wu D, Hu B, Wang RZ. Vapor compression heat pumps with pure Low-GWP refrigerants. Renew Sustain Energy Rev 2021;138. https://doi.org/10.1016/j.rser.2020.110571.
[18] Ma X, Du Y, Zhao T, Zhu T, Lei B, Wu Y. A comprehensive review of compression high-temperature heat pump steam system: status and trend. Int J Refrig 2024;164:218–42. https://doi.org/10.1016/j.ijrefrig.2024.04.024.
[19] Ji L, Shukla SK, Zuo Z, Lu X, Ji X, Wang C. An overview of the progress of new working pairs in absorption heat pumps. Energy Rep 2023;9:703–29. https://doi.org/10.1016/j.egyr.2022.11.143.
[20] Dias JMS, Costa VAF. Adsorption heat pumps for heating applications: a review of current state, literature gaps and development challenges. Renew Sustain Energy Rev 2018;98:317–27. https://doi.org/10.1016/j.rser.2018.09.026.
[21] Chua KJ, Chou SK, Yang WM. Advances in heat pump systems: a review. Appl Energy 2010;87:3611–24. https://doi.org/10.1016/j.apenergy.2010.06.014.
[22] Ally MR, Sharma V, Abdelaziz O. Exergy analysis of electrically- and thermally-driven engines to drive heat pumps: an exhaustive comparative study. Int J Refrig 2017;76:313–27. https://doi.org/10.1016/j.ijrefrig.2017.02.011.
[23] Arteconi A, Hewitt NJ, Polonara F. Domestic demand-side management (DSM): Role of heat pumps and thermal energy storage (TES) systems. Appl Therm Eng 2013;51:155–65. https://doi.org/10.1016/j.applthermaleng.2012.09.023.
[24] Arteconi A, Hewitt NJ, Polonara F. State of the art of thermal storage for demand-side management. Appl Energy 2012;93:371–89. https://doi.org/10.1016/j.apenergy.2011.12.045.
[25] Li G, Zheng X. Thermal energy storage system integration forms for a sustainable future. Renew Sustain Energy Rev 2016;62:736–57. https://doi.org/10.1016/j.rser.2016.04.076.
[26] Wüllhorst F, Reuter-Schniete J, Maier L, Müller D. Heat pump and thermal energy storage: influences of photovoltaic, the control strategy, and price assumptions on the optimal design. Renew Energy 2024;236. https://doi.org/10.1016/j.renene.2024.121409.
[27] Baeten B, Rogiers F, Helsen L. Reduction of heat pump induced peak electricity use and required generation capacity through thermal energy storage and demand response. Appl Energy 2017;195:184–95. https://doi.org/10.1016/j.apenergy.2017.03.055.
[28] Torbarina F, Lenic K, Trp A, Kirincic M. Parametric analysis of system performance and cost of heating systems with heat pump and latent thermal energy storage. Appl Therm Eng 2024;252. https://doi.org/10.1016/j.applthermaleng.2024.123717.
[29] Hirschey J, Li Z, Gluesenkamp KR, LaClair TJ, Graham S. Demand reduction and energy saving potential of thermal energy storage integrated heat pumps. Int J Refrig 2023;148:179–92. https://doi.org/10.1016/j.ijrefrig.2023.01.026.
[30] Kumar B, Awasthi A, Lee J, Jeon Y. Numerical analysis of absorber tube shapes in PCM-integrated parabolic trough solar collectors. Case Stud Therm Eng 2025;66. https://doi.org/10.1016/j.csite.2025.105783.
[31] Hameed G, Ghafoor MA, Yousaf M, Imran M, Zaman M, Elkamel A, Haq A, Rizwan M, Wilberforce T, Abdelkareem MA, Olabi AG. Low temperature phase change materials for thermal energy storage: current status and computational perspectives. Sustain Energy Technol Assessments 2022;50. https://doi.org/10.1016/j.seta.2021.101808.
[32] Mahon H, O'Connor D, Friedrich D, Hughes B. A review of thermal energy storage technologies for seasonal loops. Energy 2022;239. https://doi.org/10.1016/j.energy.2021.122207.
[33] Kou X, Giménez-Prades P, Dong Y, Yan H, Xu Z, Wang R. Combined latent heat and cold storage and supply enabled by a heat pump – the why, how, and what. Energy Convers Manag 2025;326. https://doi.org/10.1016/j.enconman.2025.119479.
[34] Kim S, Stavins RA, Garimella VS, Koronio E, Shockner T, Ziskind G, Miljkovic N, King WP. Cooling high power electronics using dynamic phase change material. Int J Heat Mass Tran 2025;237. https://doi.org/10.1016/j.ijheatmasstransfer.2024.126433.
[35] Suresh C, Awasthi A, Kumar B, kyun Im S, Jeon Y. Advances in battery thermal management for electric vehicles: a comprehensive review of hybrid PCM-metal foam and immersion cooling technologies. Renew Sustain Energy Rev 2025;208. https://doi.org/10.1016/j.rser.2024.115021.
[36] Suresh C, Kumar Hotta T, Saha SK. Phase change material incorporation techniques in building envelopes for enhancing the building thermal Comfort-A review. Energy Build 2022;268. https://doi.org/10.1016/j.enbuild.2022.112225.
[37] Awasthi A, Jeon Y. Detailed numerical analysis of heat transfer enhancement in horizontal shell-and-tube-type n-eicosane-based latent thermal energy storage system. J Energy Storage 2023;63. https://doi.org/10.1016/j.est.2023.106994.
[38] Heat pump alone and heat pump with sensible and latent heat storage Scopus database. https://www.scopus.com/pages/home?display=basic#basic. [Accessed 20 March 2025].
[39] Bouhezza A, Laouer A, Ismail KAR, Faraji H, Khuda MA, Teggar M, Lino FAM, Henríquez JR, Rodríguez D. Effective techniques for performance improvement of phase change material applications: a review. J Energy Storage 2025;105. https://doi.org/10.1016/j.est.2024.114671.
[40] Mohtasim MS, Das BK. Biomimetic and bio-derived composite Phase Change Materials for Thermal Energy Storage applications: a thorough analysis and future research directions. J Energy Storage 2024;84. https://doi.org/10.1016/j.est.2024.110945.
[41] Zhi M, Yue S, Zheng L, Su B, Fu J, Sun Q. Recent developments in solid-solid phase change materials for thermal energy storage applications. J Energy Storage 2024;89. https://doi.org/10.1016/j.est.2024.111570.
[42] Jagadeeswara Reddy V, Fairusham Ghazali M, Kumarasamy S. Innovations in phase change materials for diverse industrial applications: a comprehensive review. Results Chem 2024;8. https://doi.org/10.1016/j.rechem.2024.101552.
[43] Kumar B, Awasthi A, Suresh C, Jeon Y. Novel effective thermal conductivity numerical model for distinct shaped pure paraffins (C14–C33). J Energy Storage 2024;76. https://doi.org/10.1016/j.est.2023.109654.
[44] Zarei M, Vahidhosseini SM, Rashidi S, Rafee R, Yan WM. Review on the efficiency enhancement of solar-assisted heat pumps using nano-enhanced phase change materials (NEPCM). J Energy Storage 2025;114. https://doi.org/10.1016/j.est.2025.115804.
[45] Hassani Soukht Abandani M, Domiri Ganji D. Melting effect in triplex-tube thermal energy storage system using multiple PCMs-porous metal foam combination. J Energy Storage 2021;43. https://doi.org/10.1016/j.est.2021.103154.
[46] Mahdi JM, Najim FT, Aljubury IMA, Mohammed HI, Ben Khedher N, Alshammari NK, Cairns A, Talebizadehsardari P. Intensifying the thermal response of PCM via fin-assisted foam strips in the shell-and-tube heat storage system. J Energy Storage 2022;45. https://doi.org/10.1016/j.est.2021.103733.
[47] Gorzin M, Hosseini MJ, Rahimi M, Bahrampoury R. Nano-enhancement of phase change material in a shell and multi-PCM-tube heat exchanger. J Energy Storage 2019;22:88–97. https://doi.org/10.1016/j.est.2018.12.023.
[48] Amaral C, Vicente R, Marques PAAP, Barros-Timmons A. Phase change materials and carbon nanostructures for thermal energy storage: a literature review. Renew Sustain Energy Rev 2017;79:1212–28. https://doi.org/10.1016/j.rser.2017.05.093.
[49] Ibrahim NI, Al-Sulaiman FA, Rahman S, Yilbas BS, Sahin AZ. Heat transfer enhancement of phase change materials for thermal energy storage applications: a critical review. Renew Sustain Energy Rev 2017;74:26–50. https://doi.org/10.1016/j.rser.2017.01.169.
[50] Ali HM, ur Rehman T, Arıcı M, Said Z, Duraković B, Mohammed HI, Kumar R, Rathod MK, Buyukdagli O, Teggar M. Advances in thermal energy storage: fundamentals and applications. Prog Energy Combust Sci 2024;100. https://doi.org/10.1016/j.pecs.2023.101109.
[51] Zhang A, Xiong Y, Zhao Y, Wu Y, Xu Q, Ding Y. A review of passive building thermal management with phase-change materials. Renew Sustain Energy Rev 2025;211. https://doi.org/10.1016/j.rser.2025.115334.
[52] Su W, Darkwa J, Kokogiannakis G. Review of solid-liquid phase change materials and their encapsulation technologies. Renew Sustain Energy Rev 2015;48:373–91. https://doi.org/10.1016/j.rser.2015.04.044.
[53] Zacharias A, Baby R, Maria HJ, Thomas S. Preparation, characterization, and selection of nano-assisted phase change materials for thermal management and storage applications. Renew Sustain Energy Rev 2025;210. https://doi.org/10.1016/j.rser.2024.115195.
[54] Hirmiz R, Teamah HM, Lightstone MF, Cotton JS. Performance of heat pump integrated phase change material thermal storage for electric load shifting in building demand side management. Energy Build 2019;190:103–18. https://doi.org/10.1016/j.enbuild.2019.02.026.
[55] Lin W, Wang Q, Fang X, Gao X, Zhang Z. Experimental and numerical investigation on the novel latent heat exchanger with paraffin/expanded graphite composite. Appl Therm Eng 2018;144:836–44. https://doi.org/10.1016/j.applthermaleng.2018.08.103.
[56] Al-Yasiri Q, Szabó M. Selection of phase change material suitable for building heating applications based on qualitative decision matrix. Energy Convers Manag X 2021;12. https://doi.org/10.1016/j.ecmx.2021.100150.
[57] Li Z, Lu Y, Huang R, Chang J, Yu X, Jiang R, Yu X, Roskilly AP. Applications and technological challenges for heat recovery, storage and utilisation with latent thermal energy storage. Appl Energy 2021;283. https://doi.org/10.1016/j.apenergy.2020.116277.
[58] Hirschey J, Gluesenkamp KR, Mallow A, Graham S. Review of inorganic salt hydrates with phase change temperature in range of 5 to 60°C and material cost comparison with common waxes. https://engineering.purdue.edu/; 2018.
[59] Gu H, Chen Y, Yao X, Huang L, Zou D. Review on heat pump (HP) coupled with phase change material (PCM) for thermal energy storage. Chem Eng J 2023;455. https://doi.org/10.1016/j.cej.2022.140701.
[60] Mousa MM, Bayomy AM, Saghir MZ. Long-term performance investigation of a GSHP with actual size energy pile with PCM. Appl Therm Eng 2022;210. https://doi.org/10.1016/j.applthermaleng.2022.118381.
[61] Hu W, Song M, Jiang Y, Yao Y, Gao Y. A modeling study on the heat storage and release characteristics of a phase change material based double-spiral coiled heat exchanger in an air source heat pump for defrosting. Appl Energy 2019;236:877–92. https://doi.org/10.1016/j.apenergy.2018.12.057.
[62] Çam NY, Alptekin E, Bilir L, Ezan MA. Thermal behavior of a solar-assisted latent heat thermal energy storage unit on the heating season under variable weather conditions. J Energy Storage 2022;52. https://doi.org/10.1016/j.est.2022.104934.
[63] Yu M, Zhang C, Fan Y, Zhang X, Zhao Y. Performance study of phase change charging/discharging processes of condensing heat storage in cold regions based on a mathematical model. Appl Therm Eng 2021;182. https://doi.org/10.1016/j.applthermaleng.2020.115805.
[64] Lin Y, Fan Y, Yu M, Jiang L, Zhang X. Performance investigation on an air source heat pump system with latent heat thermal energy storage. Energy 2022;239. https://doi.org/10.1016/j.energy.2021.121898.

[65] Jin X, Zheng S, Huang G, Ck Lai A. Energy and economic performance of the heat pump integrated with latent heat thermal energy storage for peak demand shifting. Appl Therm Eng 2023;218. https://doi.org/10.1016/j.applthermaleng.2022.119337.
[66] Kelly NJ, Tuohy PG, Hawkes AD. Performance assessment of tariff-based air source heat pump load shifting in a UK detached dwelling featuring phase change-enhanced buffering. Appl Therm Eng 2014;71:809–20. https://doi.org/10.1016/j.applthermaleng.2013.12.019.
[67] Sivakumar M, Mahalingam S, Mohanraj M. Energy, financial and environmental impact analysis of solar thermal heat pump systems using a direct expansion packed bed evaporator-collector. Sol Energy 2022;232:154–68. https://doi.org/10.1016/j.solener.2021.12.059.
[68] Wu J, Feng Y, Liu C, Li H. Heat transfer characteristics of an expanded graphite/paraffin PCM-heat exchanger used in an instantaneous heat pump water heater. Appl Therm Eng 2018;142:644–55. https://doi.org/10.1016/j.applthermaleng.2018.06.087.
[69] Dogkas G, Konstantaras J, Koukou MK, Vrachopoulos M Gr, Pagkalos C, Stathopoulos VN, Pandis PK, Lymperis K, Coelho L, Rebola A. Development and experimental testing of a compact thermal energy storage tank using paraffin targeting domestic hot water production needs. Therm Sci Eng Prog 2020;19. https://doi.org/10.1016/j.tsep.2020.100573.
[70] Teamah HM, Lightstone MF. Numerical study of the electrical load shift capability of a ground source heat pump system with phase change thermal storage. Energy Build 2019;199:235–46. https://doi.org/10.1016/j.enbuild.2019.06.056.
[71] Ishaque S, Siddiqui MIH, Kim MH. Effect of heat exchanger design on seasonal performance of heat pump systems. Int J Heat Mass Tran 2020;151. https://doi.org/10.1016/j.ijheatmasstransfer.2020.119404.
[72] Bagarella G, Lazzarin R, Noro M. Sizing strategy of on-off and modulating heat pump systems based on annual energy analysis. Int J Refrig 2016;65:183–93. https://doi.org/10.1016/j.ijrefrig.2016.02.015.
[73] Mota-Babiloni A, Mateu-Royo C, Navarro-Esbrí J, Molés F, Amat-Albuixech M, Barragán-Cervera Á. Optimisation of high-temperature heat pump cascades with internal heat exchangers using refrigerants with low global warming potential. Energy 2018;165:1248–58. https://doi.org/10.1016/j.energy.2018.09.188.
[74] Saeidi R, Noorollahi Y, Esfahanian V. Numerical simulation of a novel spiral type ground heat exchanger for enhancing heat transfer performance of geothermal heat pump. Energy Convers Manag 2018;168:296–307. https://doi.org/10.1016/j.enconman.2018.05.015.
[75] Bhattad A, Sarkar J, Ghosh P. Improving the performance of refrigeration systems by using nanofluids: a comprehensive review. Renew Sustain Energy Rev 2018;82:3656–69. https://doi.org/10.1016/j.rser.2017.10.097.
[76] Kong X, Wang B, Shang Y, Li J, Li Y. Influence of different regulation modes of compressor speed on the performance of direct-expansion solar-assisted heat pump water heater. Appl Therm Eng 2020;169. https://doi.org/10.1016/j.applthermaleng.2020.115007.
[77] Bagarella G, Lazzarin R, Noro M. Annual simulation, energy and economic analysis of hybrid heat pump systems for residential buildings. Appl Therm Eng 2016;99:485–94. https://doi.org/10.1016/j.applthermaleng.2016.01.089.
[78] Busato F, Lazzarin R, Noro M. The control of renewable energies to improve the performance of multisource heat pump systems: a two-case study. Applied Sciences (Switzerland) 2021;11. https://doi.org/10.3390/app11146653.
[79] Zhang L, Feng G, Huang K, Bi Y, Chang S, Li A. Design and optimization for photovoltaic heat pump system integrating thermal energy storage and battery energy storage. Energy Build 2025;329. https://doi.org/10.1016/j.enbuild.2025.115277.
[80] Chen H, Fan W, Cai B, Li G, Wang Y, Akhlaghi YG, Wang Y, Sun Y, Jiang L. Performance and economic evaluation of a solar-air hybrid source energy heating system installed in cold region of China. J Build Eng 2022;56. https://doi.org/10.1016/j.jobe.2022.104796.
[81] Sharma A, Tyagi VV, Chen CR, Buddhi D. Review on thermal energy storage with phase change materials and applications. Renew Sustain Energy Rev 2009;13:318–45. https://doi.org/10.1016/j.rser.2007.10.005.
[82] Hiris D, Balan MC, Bode FI. A comprehensive review on enhancing seasonal energy storage systems through energy efficiency perspectives. Processes 2024;12. https://doi.org/10.3390/pr12081623.
[83] Sayegh MA, Jadwiszczak P, Axcell BP, Niemierka E, Bryś K, Jouhara H. Heat pump placement, connection and operational modes in European district heating. Energy Build 2018;166:122–44. https://doi.org/10.1016/j.enbuild.2018.02.006.
[84] Hu Y, Shen B. Development and evaluation of a multi-functional heat pump with embedded thermal storage. Appl Therm Eng 2025;267. https://doi.org/10.1016/j.applthermaleng.2025.125862.
[85] Li A, Duan S, Han R, Wang C. Investigation on the dynamic thermal storage/release of the integrated PCM solar wall embedded with an evaporator. Renew Energy 2022;200:1506–16. https://doi.org/10.1016/j.renene.2022.09.131.
[86] Jin X, Zhang H, Huang G, Lai AC. Experimental investigation on the dynamic thermal performance of the parallel solar-assisted air-source heat pump latent heat thermal energy storage system. Renew Energy 2021;180:637–57. https://doi.org/10.1016/j.renene.2021.08.067.
[87] D'Ettorre F, De Rosa M, Conti P, Testi D, Finn D. Mapping the energy flexibility potential of single buildings equipped with optimally-controlled heat pump, gas boilers and thermal storage. Sustain Cities Soc 2019;50. https://doi.org/10.1016/j.scs.2019.101689.
[88] Ouhammou B, El Rhafiki T, Lamrani B, Zeraouli Y, Kousksou T. Phase-change materials for storing heat extracted from heat pump condensers. J Energy Storage 2023;74. https://doi.org/10.1016/j.est.2023.109301.
[89] Pelella F, Zsembinszki G, Viscito L, William Mauro A, Cabeza LF. Thermo-economic optimization of a multi-source (air/sun/ground) residential heat pump with a water/PCM thermal storage. Appl Energy 2023;331. https://doi.org/10.1016/j.apenergy.2022.120398.
[90] Rashidi S, Shamsabadi H, Esfahani JA, Harmand S. A review on potentials of coupling PCM storage modules to heat pipes and heat pumps. J Therm Anal Calorim 2020;140:1655–713. https://doi.org/10.1007/s10973-019-08930-1.
[91] Youssef W, Ge YT, Tassou SA. Effects of latent heat storage and controls on stability and performance of a solar assisted heat pump system for domestic hot water production. Sol Energy 2017;150:394–407. https://doi.org/10.1016/j.solener.2017.04.065.
[92] Zhu C, Li B, Yan S, Luo Q, Li C. Experimental research on solar phase change heat storage evaporative heat pump system. Energy Convers Manag 2021;229. https://doi.org/10.1016/j.enconman.2020.113683.
[93] Li S, Xu C, Chao J, Zhang X, Gao J, Zhang C. Performance study of solar assisted heat pump using phase change slurry as heat exchange medium. Energy Convers Manag 2025;326. https://doi.org/10.1016/j.enconman.2024.119456.
[94] Wang S, Wei W, Wang W, Sun Y, Li Z, Dai C, Huang C, Tang R, Deng S. Frosting-defrosting performance variations of air source heat pumps with the type of refrigerants: R410A and R32 as an example. Appl Therm Eng 2025;262. https://doi.org/10.1016/j.applthermaleng.2024.125189.
[95] Liang C, Li X, Meng X, Shi W, Gu J, Wang B, Lv Y. A year-round efficient air source heat pump with separate and distant heat extraction for non-decaying heating capacity during defrosting. Energy 2025;315:134404. https://doi.org/10.1016/j.energy.2025.134404.
[96] Wang W, Di H, Tang R, Wei W, Sun Y, Dai C. Effect of supply water temperature on frosting performance of air source heat pump and indoor thermal environment in space heating. Build Environ 2025;267. https://doi.org/10.1016/j.buildenv.2024.112258.
[97] Lyu N, Feng G, He H, Liang C, Zhang X, Wang F, Zhu M. Impact of ambient temperature and humidity on the performance of a novel anti-frosting air source heat pump system. Energy 2025;314. https://doi.org/10.1016/j.energy.2024.134190.
[98] Qu M, Tang Y, Zhang T, Li Z, Chen J. Experimental investigation on the multi-mode heat discharge process of a PCM heat exchanger during TES based reverse cycle defrosting using in cascade air source heat pumps. Appl Therm Eng 2019;151:154–62. https://doi.org/10.1016/j.applthermaleng.2019.02.003.
[99] Essadik M, Hajabdollahi Ouderji Z, McKeown A, Lu Y, Yu Z. A multi-valve flexible heat pump system with latent thermal energy storage for defrosting operation. Energy Build 2024;321. https://doi.org/10.1016/j.enbuild.2024.114656.
[100] Chen H, Li G, Wang Y, Zhang F, Badiei A, Lu T, Yang J, Jiang L, Zhang Y. Experimental analysis of defrosting and heating performance of a solar-assisted heat pump integrated phase change energy storage. Int J Energy Res 2020;44:2173–82. https://doi.org/10.1002/er.5076.
[101] Xu Z, Han L. An experimental study on energy-storage based defrosting performance of an air source heat pump system with a micro-channel heat exchanger as outdoor coil. Appl Therm Eng 2024;240. https://doi.org/10.1016/j.applthermaleng.2023.122067.
[102] Edwards MR, Garibay-Rodriguez J, Erickson JS, Shayan M, Tan JL, Shen X, Qiu Y, Liu P. Assessing inequities in electrification via heat pumps across the US. Joule 2024. https://doi.org/10.1016/j.joule.2024.09.012.
[103] Ruan F, Xu S, Qin D, Li S, Chen P. Experimental study of air source heat pump water heater: energy, exergy, and entransy analysis. Energy and Built Environment 2023. https://doi.org/10.1016/j.enbenv.2023.10.006.
[104] Wu C, Liu F, Li X, Wang Z, Xu Z, Zhao W, Yang Y, Wu P, Xu C, Wang Y. Low-temperature air source heat pump system for heating in severely cold area: Long-term applicability evaluation. Build Environ 2022;208. https://doi.org/10.1016/j.buildenv.2021.108594.
[105] Li Z, Wei W, Wang W, Sun Y, Wang S, Lin Y, Huang C, Deng S. Experimental study on the effects of melted frost icing on the operating performances of air source heat pump. Appl Therm Eng 2024;238. https://doi.org/10.1016/j.applthermaleng.2023.122136.
[106] Hu Y, Yuill DP, Ebrahimifakhar A. The effects of outdoor air-side fouling on frost growth and heat transfer characteristics of a microchannel heat exchanger: an experimental study. Int J Heat Mass Tran 2020;151. https://doi.org/10.1016/j.ijheatmasstransfer.2020.119423.
[107] Kropas T, Streckienė G, Bielskus J. Experimental investigation of frost formation influence on an air source heat pump evaporator. Energies 2021;14. https://doi.org/10.3390/en14185737.
[108] Song M, Deng S, Dang C, Mao N, Wang Z. Review on improvement for air source heat pump units during frosting and defrosting. Appl Energy 2018;211:1150–70. https://doi.org/10.1016/j.apenergy.2017.12.022.
[109] Zhang L, Jiang Y, Dong J, Yao Y. Advances in vapor compression air source heat pump system in cold regions: a review. Renew Sustain Energy Rev 2018;81:353–65. https://doi.org/10.1016/j.rser.2017.08.009.
[110] Park C, Lee H, Hwang Y, Radermacher R. Recent advances in vapor compression cycle technologies. Int J Refrig 2015;60:118–34. https://doi.org/10.1016/j.ijrefrig.2015.08.005.
[111] Qv D, Ni L, Yao Y, Hu W. Reliability verification of a solar–air source heat pump system with PCM energy storage in operating strategy transition. Renew Energy 2015;84:46–55. https://doi.org/10.1016/j.renene.2015.07.030.
[112] Huang R, Mahvi A, James N, Kozubal E, Woods J. Evaluation of phase change thermal storage in a cascade heat pump. Appl Energy 2024;359. https://doi.org/10.1016/j.apenergy.2024.122654.

[113] Long JY, Zhu DS. Numerical and experimental study on heat pump water heater with PCM for thermal storage. Energy Build 2008;40:666–72. https://doi.org/10.1016/j.enbuild.2007.05.001.
[114] Wu P, Wang Z, Li X, Xu Z, Yang Y, Yang Q. Energy-saving analysis of air source heat pump integrated with a water storage tank for heating applications. Build Environ 2020;180. https://doi.org/10.1016/j.buildenv.2020.107029.
[115] Shan L, Martin A, Chiu JNW. Techno-economic analysis of latent heat thermal energy storage integrated heat pump for indoor heating. Energy 2024;298. https://doi.org/10.1016/j.energy.2024.131291.
[116] Du R, Wu M, Wang S, Wu S, Wang R, Li T. Integrated heat pump with phase change materials for space heating. Renew Sustain Energy Rev 2024;203. https://doi.org/10.1016/j.rser.2024.114769.
[117] Wang X, Xia L, Bales C, Zhang X, Copertaro B, Pan S, Wu J. A systematic review of recent air source heat pump (ASHP) systems assisted by solar thermal, photovoltaic and photovoltaic/thermal sources. Renew Energy 2020;146: 2472–87. https://doi.org/10.1016/j.renene.2019.08.096.
[118] Meng X, Zhou X, Li Z. Review of the coupled System of solar and air source heat pump. Energies 2024;17. https://doi.org/10.3390/en17236045.
[119] Ganesan P, Eikevik TM. Current scientific progress in solar-assisted vapor compression heat pump technology: advanced design and configuration, refrigerant, performance, economic and environmental assessments. International Journal of Thermofluids 2024;23. https://doi.org/10.1016/j.ijft.2024.100783.
[120] Yuan P, Huang F, Zhu C, Gao S, Fu P, Gao K. Review on research progress of solar coupled air source heat pump system for domestic space heating. Therm Sci Eng Prog 2024;53. https://doi.org/10.1016/j.tsep.2024.102709.
[121] Kazem HA, Chaichan MT, Al-Waeli AHA, Sopian K. A systematic review of photovoltaic/thermal applications in heat pumps systems. Sol Energy 2024;269. https://doi.org/10.1016/j.solener.2023.112299.
[122] Omojaro P, Breitkopf C. Direct expansion solar assisted heat pumps: a review of applications and recent research. Renew Sustain Energy Rev 2013;22:33–45. https://doi.org/10.1016/j.rser.2013.01.029.
[123] Lin Y, Bu Z, Yang W, Zhang H, Francis V, Li CQ. A review on the research and development of solar-assisted heat pump for buildings in China. Buildings 2022; 12. https://doi.org/10.3390/buildings12091435.
[124] Vahidhosseini SM, Rashidi S, Hsu SH, Yan WM, Rashidi A. Integration of solar thermal collectors and heat pumps with thermal energy storage systems for building energy demand reduction: a comprehensive review. J Energy Storage 2024;95. https://doi.org/10.1016/j.est.2024.112568.
[125] Zhou J, Zeng C, Wang Z, Lyu W, Tang Y, Wu D, Ji W, Yuan Y. Indirect expansion solar assisted heat pump system: a review. Sustain Energy Technol Assessments 2022;53. https://doi.org/10.1016/j.seta.2022.102409.
[126] Buker MS, Riffat SB. Solar assisted heat pump systems for low temperature water heating applications: a systematic review. Renew Sustain Energy Rev 2016;55: 399–413. https://doi.org/10.1016/j.rser.2015.10.157.
[127] Fan Y, Zhao X, Han Z, Li J, Badiei A, Akhlaghi YG, Liu Z. Scientific and technological progress and future perspectives of the solar assisted heat pump (SAHP) system. Energy 2021;229. https://doi.org/10.1016/j.energy.2021.120719.
[128] Ghasemipour S, Sameti M, Sharma MK. Annual comparative performance of direct expansion solar-assisted and air-source heat pumps for residential water heating. International Journal of Thermofluids 2024;22. https://doi.org/10.1016/j.ijft.2024.100651.
[129] Kamel RS, Fung AS, Dash PRH. Solar systems and their integration with heat pumps: a review. Energy Build 2015;87:395–412. https://doi.org/10.1016/j.enbuild.2014.11.030.
[130] Huan C, Li S, Wang F, Liu L, Zhao Y, Wang Z, Tao P. Performance analysis of a combined solar-assisted heat pump heating system in Xi'an, China. Energies 2019;12. https://doi.org/10.3390/en12132515.
[131] Ma J, Zhu X, Fan H, Su J, Lu Y, Zhang Z. Size and match of the collector-evaporator for direct-expansion solar assisted heat pumps using potential alternative refrigerants. Int J Refrig 2025;171:253–66. https://doi.org/10.1016/j.ijrefrig.2024.12.002.
[132] Yang LW, Xu RJ, Hua N, Xia Y, Bin Zhou W, Yang T, Belyayev Y, Wang HS. Review of the advances in solar-assisted air source heat pumps for the domestic sector. Energy Convers Manag 2021;247. https://doi.org/10.1016/j.enconman.2021.114710.
[133] Badiei A, Golizadeh Akhlaghi Y, Zhao X, Shittu S, Xiao X, Li J, Fan Y, Li G. A chronological review of advances in solar assisted heat pump technology in 21st century. Renew Sustain Energy Rev 2020;132. https://doi.org/10.1016/j.rser.2020.110132.
[134] Shi GH, Aye L, Li D, Du XJ. Recent advances in direct expansion solar assisted heat pump systems: a review. Renew Sustain Energy Rev 2019;109:349–66. https://doi.org/10.1016/j.rser.2019.04.044.
[135] Sahin E, Adiguzel N. Experimental analysis of the effects of climate conditions on heat pump system performance. Energy 2022;243. https://doi.org/10.1016/j.energy.2021.123037.
[136] Zhang S, Liu S, Shen Y, Shukla A, Mazhar AR, Chen T. Critical review of solar-assisted air source heat pump in China. Renew Sustain Energy Rev 2024;193. https://doi.org/10.1016/j.rser.2024.114291.
[137] Jie J, Jingyong C, Wenzhu H, Yan F. Experimental study on the performance of solar-assisted multi-functional heat pump based on enthalpy difference lab withsolar simulator. Renew Energy 2015;75:381–8. https://doi.org/10.1016/j.renene.2014.09.054.
[138] Yang LW, Xu RJ, Bin Zhou W, Li Y, Yang T, Wang HS. Investigation of solar assisted air source heat pump heating system integrating compound parabolic concentrator-capillary tube solar collectors. Energy Convers Manag 2023;277. https://doi.org/10.1016/j.enconman.2022.116607.
[139] Murugan M, Saravanan A, Elumalai PV, Kumar P, Ahamed Saleel C, Samuel OD, Setiyo M, Enweremadu CC, Afzal A. An overview on energy and exergy analysis of solar thermal collectors with passive performance enhancers. Alex Eng J 2022;61: 8123–47. https://doi.org/10.1016/j.aej.2022.01.052.
[140] Gagliano A, Tina GM, Aneli S, Nižetić S. Comparative assessments of the performances of PV/T and conventional solar plants. J Clean Prod 2019;219: 304–15. https://doi.org/10.1016/j.jclepro.2019.02.038.
[141] Beltrán F, Sommerfeldt N, Reichl C, Madani H. Cold solar: PVT heat exchanger designs for heat pump integration. Appl Therm Eng 2025;261. https://doi.org/10.1016/j.applthermaleng.2024.125020.
[142] Zhang L, He W, Zhu J, Liu X, Hu Z, Yang C, Meng Q, Wang S, Li M, Zhang X, Zhang C. Experimental study of dual-source heat pump coupled with water-cooled photovoltaic/thermal system. Appl Therm Eng 2025;258. https://doi.org/10.1016/j.applthermaleng.2024.124758.
[143] Dong X, Liu Y, Pu Z, Zhang L. Experimental investigation of an off-grid photovoltaic heat pump collection system with heat collecting as a core. Appl Therm Eng 2025;260. https://doi.org/10.1016/j.applthermaleng.2024.125004.
[144] Zou W, Yu G, Du X, Wu H. Dynamic performance of photovoltaic thermal-heat pump system with connection configurations. Renew Energy 2025;242. https://doi.org/10.1016/j.renene.2025.122512.
[145] Bisengimana E, Zhou J, Binama M, Nyiranzeyimana G, Yuan Y. Numerical investigation of PVT coverage on an integrated building-solar-heat pump system: technical and economic study. Sol Energy 2023;249:507–20. https://doi.org/10.1016/j.solener.2022.12.005.
[146] Chhugani B, Pärisch P, Helmling S, Giovannetti F. Comparison of PVT - heat pump systems with reference systems for the energy supply of a single-family house. Solar Energy Advances 2023;3. https://doi.org/10.1016/j.seja.2022.100031.
[147] Vallati A, Ocłoń P, Colucci C, Mauri L, de Lieto Vollaro R, Taler J. Energy analysis of a thermal system composed by a heat pump coupled with a PVT solar collector. Energy 2019;174:91–6. https://doi.org/10.1016/j.energy.2019.02.152.
[148] Da J, Li M, Li G, Wang Y, Zhang Y. Simulation and experiment of a photovoltaic—air source heat pump system with thermal energy storage for heating and domestic hot water supply. Build Simulat 2023;16:1897–913. https://doi.org/10.1007/s12273-022-0960-6.
[149] Navakrishnan S, Vengadesan E, Senthil R, Dhanalakshmi S. An experimental study on simultaneous electricity and heat production from solar PV with thermal energy storage. Energy Convers Manag 2021;245. https://doi.org/10.1016/j.enconman.2021.114614.
[150] Zanetti E, Bordignon S, Conte R, Bisi A, Azzolin M, Zarrella A. Experimental and numerical analysis of a CO2 dual-source heat pump with PVT evaporators for residential heating applications. Appl Therm Eng 2023;233. https://doi.org/10.1016/j.applthermaleng.2023.121165.
[151] Wang X, Li T, Yu Y, Liu X, Liu Y, Wang S, Li G, Mao Q. Energy saving and economic analysis of a novel PV/T coupled multi-source heat pump heating system with phase change storage: a case study in cold zone in China. Energy Convers Manag 2024;312. https://doi.org/10.1016/j.enconman.2024.118574.
[152] Choi HU, Choi KH. Numerical study on the performance of a solar-assisted heat pump coupled with a photovoltaic-thermal air heater. Energy 2023;285. https://doi.org/10.1016/j.energy.2023.129480.
[153] Gao J, Li S, Wu F, Jiang L, Zhao Y, Zhang X. Study on efficient heating method by solar coupled air source heat pump system with phase change heat storage in severe cold region. Appl Energy 2024;367. https://doi.org/10.1016/j.apenergy.2024.123206.
[154] Zhang S, Liu S, Wang J, Li Y, Yu Z. Analysis of a solar-assisted heat pump system with hybrid energy storage for space heating. Appl Therm Eng 2023;231. https://doi.org/10.1016/j.applthermaleng.2023.120884.
[155] Zheng X, Tang Z, Wang Y, Liu H. Performance of the air source heat pump assisted solar heating system combined with PCM floor. Appl Therm Eng 2024;239. https://doi.org/10.1016/j.applthermaleng.2023.122115.
[156] Yıldız Ç, Seçilmiş M, Arıcı M, Mert MS, Nižetić S, Karabay H. An experimental study on a solar-assisted heat pump incorporated with PCM based thermal energy storage unit. Energy 2023;278. https://doi.org/10.1016/j.energy.2023.128035.
[157] Gao J, Zhao Y, Wu F, Adnouni M, Sun Y, Li S, Yu Z, Zhang X. Experimental investigation on efficient heating method of solar composite heat pump based on evaporative thermal accumulator. Energy 2025;317. https://doi.org/10.1016/j.energy.2025.134627.
[158] Khan MMA, Ibrahim NI, Mahbubul IM, Ali H Muhammad, Saidur R, Al-Sulaiman FA. Evaluation of solar collector designs with integrated latent heat thermal energy storage: a review. Sol Energy 2018;166:334–50. https://doi.org/10.1016/j.solener.2018.03.014.
[159] Ying S, Zhang X, Wu Y, Pan Z. Solar photovoltaic/thermal(PV/T)systems with/without phase change materials (PCMs): a review. J Energy Storage 2024;89. https://doi.org/10.1016/j.est.2024.111582.
[160] Khanlari A, Aytaç İ, Tuncer AD, Variyenli Hİ, Şahin HN. Improving the performance of a PCM integrated solar air collector by adding porous fins over the bottom side of the absorber: a transient CFD study. J Energy Storage 2024;90. https://doi.org/10.1016/j.est.2024.111847.
[161] Wang H, Xie S. The effect of annular phase-change material layer on the thermal behavior of solar collector tube. J Energy Storage 2022;52. https://doi.org/10.1016/j.est.2022.104948.
[162] Bejan AS, Croitoru C, Bode F, Teodosiu C, Catalina T. Experimental investigation of an enhanced transpired air solar collector with embodied phase changing materials. J Clean Prod 2022;336. https://doi.org/10.1016/j.jclepro.2022.130398.

[163] Palacio M, Rincón A, Carmona M. Experimental comparative analysis of a flat plate solar collector with and without PCM. Sol Energy 2020;206:708–21. https://doi.org/10.1016/j.solener.2020.06.047.
[164] Mao Q. Recent developments in geometrical configurations of thermal energy storage for concentrating solar power plant. Renew Sustain Energy Rev 2016;59: 320–7. https://doi.org/10.1016/j.rser.2015.12.355.
[165] Abdulateef AM, Mat S, Abdulateef J, Sopian K, Al-Abidi AA. Geometric and design parameters of fins employed for enhancing thermal energy storage systems: a review. Renew Sustain Energy Rev 2018;82:1620–35. https://doi.org/10.1016/j.rser.2017.07.009.
[166] He X, Qiu J, Wang W, Hou Y, Ayyub M, Shuai Y. A review on numerical simulation, optimization design and applications of packed-bed latent thermal energy storage system with spherical capsules. J Energy Storage 2022;51. https://doi.org/10.1016/j.est.2022.104555.
[167] Jain S, Kumar KR, Rakshit D. Heat transfer augmentation in single and multiple (cascade) phase change materials based thermal energy storage: research progress, challenges, and recommendations. Sustain Energy Technol Assessments 2021;48. https://doi.org/10.1016/j.seta.2021.101633.
[168] Panchal JM, Modi KV, Patel VJ. Development in multiple-phase change materials cascaded low-grade thermal energy storage applications: a review. Clean Eng Technol 2022;8. https://doi.org/10.1016/j.clet.2022.100465.
[169] Jain S, Kumar KR, Rakshit D, Premachandran B, Reddy KS. Cyclic performance assessment of medium-temperature cascade thermal energy storage. J Energy Storage 2023;68. https://doi.org/10.1016/j.est.2023.107662.
[170] Suresh C, Awasthi A, Lee D, Jeon Y. Energy and economic evaluation of combined sensible-latent thermal energy storage system with various volume fractions of phase change material. Alex Eng J 2024;98:344–55. https://doi.org/10.1016/j.aej.2024.04.044.
[171] Tat SA, Muthukumar P. Development of a lab-scale combined sensible and latent heat storage system: a numerical and experimental study. Int J Therm Sci 2025; 208. https://doi.org/10.1016/j.ijthermalsci.2024.109387.
[172] Zhang S, Li Y, Yan Y. Hybrid sensible-latent heat thermal energy storage using natural stones to enhance heat transfer: energy, exergy, and economic analysis. Energy 2024;286. https://doi.org/10.1016/j.energy.2023.129530.
[173] Pereira da Cunha J, Eames P. Thermal energy storage for low and medium temperature applications using phase change materials - a review. Appl Energy 2016;177:227–38. https://doi.org/10.1016/j.apenergy.2016.05.097.
[174] Shamsi H, Boroushaki M, Geraei H. Performance evaluation and optimization of encapsulated cascade PCM thermal storage. J Energy Storage 2017;11:64–75. https://doi.org/10.1016/j.est.2017.02.003.
[175] Suresh C, Saini RP. Experimental study on combined sensible-latent heat storage system for different volume fractions of PCM. Sol Energy 2020;212:282–96. https://doi.org/10.1016/j.solener.2020.11.013.
[176] Ni L, Dong J, Yao Y, Shen C, Qv D, Zhang X. A review of heat pump systems for heating and cooling of buildings in China in the last decade. Renew Energy 2015; 84:30–45. https://doi.org/10.1016/j.renene.2015.06.043.
[177] Jung Y, Oh J, Han U, Lee H. A comprehensive review of thermal potential and heat utilization for water source heat pump systems. Energy Build 2022;266. https://doi.org/10.1016/j.enbuild.2022.112124.
[178] Zhao Z, Zhang Y, Mi H, Zhou Y, Zhang Y. Experimental research of a water-source heat pump water heater system. Energies 2018;11. https://doi.org/10.3390/en11051205.
[179] Cho Y, Yun R. A raw water source heat pump air-conditioning system. Energy Build 2011;43:3068–73. https://doi.org/10.1016/j.enbuild.2011.07.028.
[180] Cardemil JM, Schneider W, Behzad M, Starke AR. Thermal analysis of a water source heat pump for space heating using an outdoor pool as a heat source. J Build Eng 2021;33. https://doi.org/10.1016/j.jobe.2020.101581.
[181] Zheng W, Ye T, You S, Zhang H. The thermal performance of seawater-source heat pump systems in areas of severe cold during winter. Energy Convers Manag 2015; 90:166–74. https://doi.org/10.1016/j.enconman.2014.10.050.
[182] Büyükalaca O, Ekinci F, Yilmaz T. Experimental investigation of Seyhan River and dam lake as heat source-sink for a heat pump. Energy 2003;28:157–69. https://doi.org/10.1016/S0360-5442(02)00088-9.
[183] Jung Y, Kim J, Kim H, Nam Y, Cho H, Lee H. Comprehensive multi-criteria evaluation of water source heat pump systems in terms of building type, water source, and water intake distance. Energy Build 2021;236. https://doi.org/10.1016/j.enbuild.2021.110765.
[184] Shin HH, Kim K, Lee M, Han C, Kim Y. Maximized thermal energy utilization of surface water-source heat pumps using heat source compensation strategies under low water temperature conditions. Energy 2024;288. https://doi.org/10.1016/j.energy.2023.129700.
[185] Olabi AG, Mahmoud M, Obaideen K, Sayed ET, Ramadan M, Abdelkareem MA. Ground source heat pumps: recent progress, applications, challenges, barriers, and role in achieving sustainable development goals based on bibliometric analysis. Therm Sci Eng Prog 2023;41. https://doi.org/10.1016/j.tsep.2023.101851.
[186] Javadi H, Mousavi Ajarostaghi SS, Rosen MA, Pourfallah M. Performance of ground heat exchangers: a comprehensive review of recent advances. Energy 2019;178:207–33. https://doi.org/10.1016/j.energy.2019.04.094.
[187] Lucia U, Simonetti M, Chiesa G, Grisolia G. Ground-source pump system for heating and cooling: review and thermodynamic approach. Renew Sustain Energy Rev 2017;70:867–74. https://doi.org/10.1016/j.rser.2016.11.268.
[188] Kim MJ, Lee SR, Yoon S, Jeon JS. An applicable design method for horizontal spiral-coil-type ground heat exchangers. Geothermics 2018;72:338–47. https://doi.org/10.1016/j.geothermics.2017.12.010.
[189] Lv J, Wei Z, Zhang J. Running and economy performance analysis of ground source heat pump with thermal energy storage devices. Energy Build 2016;127: 1108–16. https://doi.org/10.1016/j.enbuild.2016.06.072.
[190] Ayaz H, Faizal M, Bouazza A. Energy, economic, and carbon emission analysis of a residential building with an energy pile system. Renew Energy 2024;220. https://doi.org/10.1016/j.renene.2023.119712.
[191] Sadeghi H, Singh RM. Driven precast concrete geothermal energy piles: current state of knowledge. Build Environ 2023;228. https://doi.org/10.1016/j.buildenv.2022.109790.
[192] Fadejev J, Simson R, Kurnitski J, Haghighat F. A review on energy piles design, sizing and modelling. Energy 2017;122:390–407. https://doi.org/10.1016/j.energy.2017.01.097.
[193] Khalil A, Attom M, Khan Z, Astillo PV, El-Kadri OM. Recent advancements in geothermal energy piles performance and design. Energies 2024;17. https://doi.org/10.3390/en17143386.
[194] Elkezza O, Alhawat M, Mohamed M, Khan A. Experimental investigation on the use of PCM heat exchangers in Geo-energy piles and walls. Geothermics 2024; 119. https://doi.org/10.1016/j.geothermics.2024.102950.
[195] Anis Akrouch G, Sánchez M, Briaud JL. Thermal performance and economic study of an energy piles system under cooling dominated conditions. Renew Energy 2020;147:2736–47. https://doi.org/10.1016/j.renene.2018.11.101.
[196] Ma Q, Fan J, Liu H. Energy pile-based ground source heat pump system with seasonal solar energy storage. Renew Energy 2023;206:1132–46. https://doi.org/10.1016/j.renene.2023.02.116.
[197] Shukla S, Bayomy AM, Antoun S, Mwesigye A, Leong WH, Dworkin SB. Performance characterization of novel caisson-based thermal storage for ground source heat pumps. Renew Energy 2021;174:43–54. https://doi.org/10.1016/j.renene.2021.04.075.
[198] Fei W, Bandeira Neto LA, Dai S, Cortes DD, Narsilio GA. Numerical analyses of energy screw pile filled with phase change materials. Renew Energy 2023;202: 865–79. https://doi.org/10.1016/j.renene.2022.12.008.
[199] Cao Z, Zhang G, Liu Y, Zhao X, Li C. Influence of backfilling phase change material on thermal performance of precast high-strength concrete energy pile. Renew Energy 2022;184:374–90. https://doi.org/10.1016/j.renene.2021.11.100.
[200] Al-Sayyab AKS, Mota-Babiloni A, Navarro-Esbrí J. Renewable and waste heat applications for heating, cooling, and power generation based on advanced configurations. Energy Convers Manag 2023;291. https://doi.org/10.1016/j.enconman.2023.117253.
[201] Law R, Harvey A, Reay D. Opportunities for low-grade heat recovery in the UK food processing industry. Appl Therm Eng 2013;53:188–96. https://doi.org/10.1016/j.applthermaleng.2012.03.024.
[202] Tan Z, Feng X, Wang Y. Performance comparison of different heat pumps in low-temperature waste heat recovery. Renew Sustain Energy Rev 2021;152. https://doi.org/10.1016/j.rser.2021.111634.
[203] Cho K, Chang H, Jung Y, Yoon Y. Economic analysis of data center cooling strategies. Sustain Cities Soc 2017;31:234–43. https://doi.org/10.1016/j.scs.2017.03.008.
[204] Yuan X, Liang Y, Hu X, Xu Y, Chen Y, Kosonen R. Waste heat recoveries in data centers: a review. Renew Sustain Energy Rev 2023;188. https://doi.org/10.1016/j.rser.2023.113777.
[205] Jang Y, Lee D, Kim J, Ham SH, Kim Y. Performance characteristics of a waste-heat recovery water-source heat pump system designed for data centers and residential area in the heating dominated region. J Build Eng 2022;62. https://doi.org/10.1016/j.jobe.2022.105416.
[206] Wang S, Qu R, Zhang X, Li Y, Chen J. Thermal performance analysis of ground source heat pump system for low-temperature waste heat recovery storage. Case Stud Therm Eng 2022;35. https://doi.org/10.1016/j.csite.2022.102131.
[207] Ma J, Zhang X, Yu J, Wei P. Thermo-economic assessments on building heating by a sewage source heat pump coupled with heat storage system. Therm Sci Eng Prog 2024;53. https://doi.org/10.1016/j.tsep.2024.102756.
[208] Said Z, Pandey AK, Tiwari AK, Kalidasan B, Jamil F, Thakur AK, Tyagi VV, Sarı A, Ali HM. Nano-enhanced phase change materials: fundamentals and applications. Prog Energy Combust Sci 2024;104. https://doi.org/10.1016/j.pecs.2024.101162.
[209] Ji C, Waqas H, Liu D, Kang C, Muhammad T. Melting performance improvement of phase change materials with thermal energy storage unit using nanoparticles. Case Stud Therm Eng 2024;61. https://doi.org/10.1016/j.csite.2024.104892.
[210] Paul UK, Mohtasim MS, Kibria MG, Das BK. Nano-material based composite phase change materials and nanofluid for solar thermal energy storage applications: featuring numerical and experimental approaches. J Energy Storage 2024;98. https://doi.org/10.1016/j.est.2024.113032.
[211] Aziz A, Waheed W, Mourad A, Aissa A, Younis O, Abu-Nada E, Alazzam A. Contemporary nano enhanced phase change materials: classification and applications in thermal energy management systems. J Energy Storage 2024;75. https://doi.org/10.1016/j.est.2023.109579.
[212] Chinnasamy V, Heo J, Jung S, Lee H, Cho H. Shape stabilized phase change materials based on different support structures for thermal energy storage applications–A review. Energy 2023;262. https://doi.org/10.1016/j.energy.2022.125463.
[213] Huang X, Chen X, Li A, Atinafu D, Gao H, Dong W, Wang G. Shape-stabilized phase change materials based on porous supports for thermal energy storage applications. Chem Eng J 2019;356:641–61. https://doi.org/10.1016/j.cej.2018.09.013.
[214] Xiao Y, Li T, Yang Y, Lin J, Sheng X, Huang J, Li T, Lu X, Xie D. Exploring flame-retardant, shape-stabilized multi-functional composite phase change materials.

Sol Energy Mater Sol Cell 2025;282. https://doi.org/10.1016/j.solmat.2024.113369.
[215] Shoeibi S, Jamil F, Parsa SM, Mehdi S, Kargarsharifabad H, Mirjalily SAA, Guo W, Ngo HH, Ni BJ, Khiadani M. Recent advancements in applications of encapsulated phase change materials for solar energy systems: a state of the art review. J Energy Storage 2024;94. https://doi.org/10.1016/j.est.2024.112401.
[216] Haddad Z, Buonomo B, Abu-Nada E, Manca O. A comprehensive review on the properties of micro/nano-encapsulated phase change materials: Single- to multi-layered shells. Renew Sustain Energy Rev 2024;205. https://doi.org/10.1016/j.rser.2024.114826.
[217] Ghasemi K, Tasnim S, Mahmud S. PCM, nano/microencapsulation and slurries: a review of fundamentals, categories, fabrication, numerical models and applications. Sustain Energy Technol Assessments 2022;52. https://doi.org/10.1016/j.seta.2022.102084.
[218] Huang Y, Stonehouse A, Abeykoon C. Encapsulation methods for phase change materials – a critical review. Int J Heat Mass Tran 2023;200. https://doi.org/10.1016/j.ijheatmasstransfer.2022.123458.
[219] Palacios A, Navarro-Rivero ME, Zou B, Jiang Z, Harrison MT, Ding Y. A perspective on Phase Change Material encapsulation: guidance for encapsulation design methodology from low to high-temperature thermal energy storage applications. J Energy Storage 2023;72. https://doi.org/10.1016/j.est.2023.108597.
[220] Rashid FL, Al-Obaidi MA, Dhaidan NS, Hussein AK, Ali B, Ben Hamida MB, Younis O. Bio-based phase change materials for thermal energy storage and release: a review. J Energy Storage 2023;73. https://doi.org/10.1016/j.est.2023.109219.
[221] Benhorma A, Bensenouci A, Teggar M, Ismail KAR, Arıcı M, Mezaache E, Laouer A, Lino FAM. Prospects and challenges of bio-based phase change materials: an up to date review. J Energy Storage 2024;90. https://doi.org/10.1016/j.est.2024.111713.
[222] Simonsen G, Ravotti R, O'Neill P, Stamatiou A. Biobased phase change materials in energy storage and thermal management technologies. Renew Sustain Energy Rev 2023;184. https://doi.org/10.1016/j.rser.2023.113546.
[223] Wu WY, Gao M, Yeo Jueyuan R, Lin M, Wang S, Thitsartarn W, Zhang X, Kai D, Wang P, Qu Z, Xu J, Jun Loh X, Zhu Q. Plant oil-based phase change materials for sustainable thermal energy storage: a review. Fuel 2024;378. https://doi.org/10.1016/j.fuel.2024.132940.
[224] Devkota K, Rasul MG, Chowdhury AA, Azad AK. Recent advancements in low-energy buildings: integrating bio-phase change materials and rooftop greenery systems. J Build Eng 2025;101. https://doi.org/10.1016/j.jobe.2025.111790.
[225] Bayram M, Ustaoglu A, Kursuncu B, Hekimoglu G, Sari A, Uğur LO, Subasi S, Gencel O, Ozbakkaloglu T. 3D-printed polylactic acid-microencapsulated phase change material composites for building thermal management. Renew Sustain Energy Rev 2024;191. https://doi.org/10.1016/j.rser.2023.114150.
[226] Freeman TB, Foster KEO, Troxler CJ, Irvin CW, Aday A, Boetcher SKS, Mahvi A, Smith MK, Odukomaiya A. Advanced materials and additive manufacturing for phase change thermal energy storage and management: a review. Adv Energy Mater 2023;13. https://doi.org/10.1002/aenm.202204208.
[227] Liu P, Chen X, Wang G. Advanced 3D-printed phase change materials. Matter 2021;4:3374–6. https://doi.org/10.1016/j.matt.2021.10.002.
[228] Yu M, Li S, Zhang X, Zhao Y. Techno-economic analysis of air source heat pump combined with latent thermal energy storage applied for space heating in China. Appl Therm Eng 2021;185. https://doi.org/10.1016/j.applthermaleng.2020.116434.
[229] Qu M, Yan X, Wang H, Hei Y, Liu H, Li Z. Energy, exergy, economic and environmental analysis of photovoltaic/thermal integrated water source heat pump water heater. Renew Energy 2022;194:1084–97. https://doi.org/10.1016/j.renene.2022.06.010.
[230] Pochwała S, Anweiler S, Tańczuk M, Klementowski I, Przysiężniuk D, Adrian Ł, McNamara G, Stevanović Ž. Energy source impact on the economic and environmental effects of retrofitting a heritage building with a heat pump system. Energy 2023;278. https://doi.org/10.1016/j.energy.2023.128037.
[231] Maddah S, Deymi-Dashtebayaz M, Maddah O. 4E analysis of thermal recovery potential of industrial wastewater in heat pumps: an invisible energy resource from the iranian casting industry sector. J Clean Prod 2020;265. https://doi.org/10.1016/j.jclepro.2020.121824.
[232] Aguilar F, Crespí-Llorens D, Quiles PV. Environmental benefits and economic feasibility of a photovoltaic assisted heat pump water heater. Sol Energy 2019;193:20–30. https://doi.org/10.1016/j.solener.2019.09.032.
[233] Biglarian H, Saidi MH, Abbaspour M. Economic and environmental assessment of a solar-assisted ground source heat pump system in a heating-dominated climate. Int J Environ Sci Technol 2019;16:3091–8. https://doi.org/10.1007/s13762-018-1673-3.