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Review article

Energy storage-integrated ground-source heat pumps for heating and cooling applications: A systematic review

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ABSTRACT

Renewable energy-based ground source heat pump (GSHP) systems have gained traction as cost-effective and environmentally sustainable alternatives for heating and cooling applications in residential, commercial, and civic buildings. However, their prolonged operation may lead to a decline in the geothermal potential of the soil and its thermal imbalance. The integration of thermal energy storage (TES) systems with GSHPs can mitigate these issues by balancing energy supply and demand, providing flexibility to meet heating and cooling demand during peak hours, preserving energy during off-peak hours, and optimising overall system efficiency. In recent years, there has been a significant increase in experimental, numerical, and theoretical studies investigating various TES-assisted GSHP configurations under different operational conditions and climate scenarios. These integrated systems may consider different sensible heat, latent heat, and sensible-latent heat-based TES methods. In this context, this paper presents a comprehensive overview of recent progress in TES-assisted GSHP systems. The main objectives of this work are to bridge the knowledge gap on these integrated systems, provide clarity on the adopted terminology, and highlight advantages and disadvantages of the different configurations presented in the literature. This review is expected to offer valuable insight for researchers and partitioners in the field of TES-assisted GSHPs and guide future research and development efforts in the area—ultimately supporting the path towards decarbonisation of heat (including space cooling) and meeting net-zero targets.

Nomenclature

Symbols	
a_m	melted fraction
c_p	specific heat
h	enthalpy
m	mass
Q	energy
T	temperature

Subscripts	
i	initial
f	final
lp	liquid phase
m	melting
sp	solid phase

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(*continued*)

Subscripts	

Abbreviations	
ATES	Aquifer thermal energy storage
BHE	Borehole heat exchanger
BTES	Borehole thermal energy storage
COP	Coefficient of performance
DSHP	Dual source heat pump
GCHP	Ground-coupled heat pump
GHE	Ground heat exchanger
GSHP	Ground-source heat pump
HGHE	Horizontal ground heat exchanger
HGSHP	Hybrid ground-source heat pump
HE	Heat exchanger
LHTES	Latent heat thermal energy storage
MPCM	Micro-encapsulated phase change material
NOS	Not otherwise specified
PCM	Phase change material

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Abbreviations	
PTES	Pit thermal energy storage
PVT	Photovoltaic thermal
SAGSHP	Solar assisted ground-source heat pump
SCOP	Seasonal coefficient of performance
SHTES	Sensible heat thermal energy storage
SSPCM	Shape stabilised phase change material
TES	Thermal energy storage
TTES	Tank thermal energy storage
UTB	Underground thermal battery
VBGHE	Vertical borehole ground heat exchanger

1. Introduction

Urbanisation, characterised by an increase in population and improved living standards, has led to the expansion of cities and a strain on infrastructure for housing, transportation, and energy systems. While urbanisation has brought economic and social progress, it has also led to a significant rise in energy consumption. The energy sector is a significant contributor to greenhouse gas emissions, with estimates indicating that it is responsible for over two-thirds of the total global emissions [1]. Particularly, the building sector plays a significant role, accounting for 30 % of the global final energy consumption and 27 % of the total energy sector emissions [2]. However, this contribution can be reduced by implementing more efficient and cleaner heating and cooling technologies.

Heat pumps are being increasingly recognised as a vital technology for reducing carbon emissions in the heating sector and have received significant policy support in several countries. As of 2021, there were 190 million heat pump units in operation worldwide, and their usage has been steadily increasing, particularly in primary heating markets such as North America, Europe, and Asia [3–5]. In addition to climate goals, energy security is also a major driver for heat pump adoption in the European Union. In their report "Net Zero by 2050", the International Energy Agency has set a target to meet 50 % of heating demand with heat pumps by 2045, which will require improving the efficiency of existing heat pump systems [6,7].

With warmer summers being expected in several countries, the need for cooling buildings is growing and this is an aspect that must not be overlooked [8]. For instance, in the UK, the cooling demand in buildings accounts for up to 10 % of the country's electricity usage [9], while this figure increases to about 20 % of total electricity consumption worldwide [10]. However, installing individual split air-conditioning systems could exacerbate the already high peak cooling loads, putting a strain on the electricity system. Thus, it is necessary to adopt a more sustainable approach to cooling that considers changing lifestyles and the expected rise in cooling demand [11]. The adoption of heat pump technology to contribute towards meeting cooling demand, due to its reduced carbon footprint, has gained significant attention.

Heat pumps are devices that use electrical energy to transfer heat from a colder space to a warmer space. When used for heating, the heat is transferred from the outdoor to the indoor, while an opposite process is followed for cooling [12]. Geothermal heat pumps, also known as ground-source heat pumps (GSHPs), earth energy systems, or ground-source systems, utilise a closed-loop system that combines a heat pump with a ground heat exchanger (GHE). In certain cases, an open-loop system can be employed, utilising ground water. These systems harness the earth's heat as a source during heating mode and as a sink during cooling mode. A fluid such as water or a water-antifreeze mixture is used to transfer heat from the ground to the heat pump. With borehole heat exchangers (BHEs), GSHPs may offer heating and cooling solutions in a wide range of locations while providing a high degree of adaptability to meet diverse thermal demands and requirements [13,14].

GSHP systems possess a higher coefficient of performance (COP) in comparison to traditional heat, ventilation and air conditioning systems. This can be attributed to the tendency of the subterranean environment to exhibit elevated thermal energy for heating and lower thermal energy for cooling, in addition to a reduced fluctuation in temperature as compared to the ambient air [13]. However, despite the potential benefits of geothermal heat pumps, their efficiency can be affected by the presence of unbalanced loads. Continuous operation under unbalanced load conditions may lead to a reduction in the geothermal potential for heat extraction or rejection which, in turn, may reduce the overall performance of the heat pump [15–18]. For instance, in areas with severe cold weather, if the cooling load in the summer is not sufficient to balance the heating load in the winter, an irreversible decrease in underground soil temperature may result, leading to a significant reduction in heat pump efficiency.

Recent references have examined the integration of hybrid ground-coupled heat pump (GCHP) systems. These references, briefly discussed next, provide detailed analyses of the potential benefits and challenges of integrating various energy sources, such as solar energy, conventional air-conditioning systems, cooling towers, dehumidification systems, and the heat recovery systems. Soni et al. [19] presented a comprehensive review on hybrid GCHPs, including the integration of GSHPs and air heat pumps with passive energy sources for space heating and cooling. Zhai et al. [20] summarised literature findings on the potential of several integrated approaches for hybrid ground-source heat pump (HGSHP) systems. Xu et al. [21] conducted a review of different HGSHPs to address the problem of soil thermal imbalance. Puttige et al. [22] presented a review on the modelling and optimisation of HGSHPs for district heating and cooling. Nouri et al. [23] presented a general technology overview of solar-assisted GCHP systems in a review article. Onder and Arif [24] analysed the literature studies addressing the energy and exergy analysis of solar-assisted ground-source heat pump (SAGSHP) systems. Tian et al. [25] presented a review on the principles, configurations, and functions of hybrid photovoltaic thermal ground-source heat pumps (PVT-GSHPs), where these were classified as hybrid PVT-GSHP with PVT for direct heating, hybrid PVT-GSHP with PVT for a temperature increase, hybrid PVT-GSHP with multiple energy sources, and HGSHP with energy storage/borehole recharge.

Integration of supplementary heating and cooling sources into GSHP systems is a relatively new approach that may relieve the issue of unbalanced loads. Heating source-assisted HGSHPs are based on a solar collector, a PVT plant and fossil fuel sources, while cooling source-assisted HGSHPs integrate a cooling tower. However, in addition to prevent thermal imbalance of the soil, the integration of thermal energy storage (TES) units into GSHP systems can effectively manage energy demand and supply by enabling the conservation of energy during off-peak hours and energy utilisation during peak hours. Among the available TES technologies, sensible heat and latent heat-based TES systems have been commonly considered in conjunction with GSHPs [14].

Despite the consensus that incorporating heat pump technology and TES systems is key for the decarbonisation of heating and cooling systems, meeting net-zero targets by 2050 may be hindered by the lack of progress in decarbonising residential dwellings [26]. In part, this may be attributed to the ambiguity behind the available heat pump technologies, the unawareness of their thermal performance, and the role that TES-assisted configurations, which may affect their suitability to be deployed in existing systems. In addition, replacing conventional heat provision methods with heat pump systems in ageing dwellings may be unfeasible for the general population: this replacement process may be expensive, it may require considerable changes to the existing infrastructure, and it may cause significant disruption. These obstacles prevent the wide adoption of heat pump technology [27].

This paper presents a comprehensive systematic review of the recent advancements and developments in the field of TES-assisted GSHPs for various operational and environmental conditions. The primary objective of this review is to bridge the knowledge gap pertaining to TES-assisted GSHPs and help clarify any ambiguities that may slow down the path towards decarbonisation of heat (including space cooling) and meeting net-zero targets. The literature studies have been classified into three categories depending on the type of TES system adopted: sensible heat, latent heat, and a combination of both. The sensible heat-based systems include soil and water integrated GSHPs, while ice-based and phase change material (PCM)-based systems are discussed within the latent heat-based systems. For the case of sensible-latent coupled systems, PCM-water and PCM-soil based systems are discussed. For clarity, the overall structure of the study is summarised in Fig. 1.

The review also includes a systematic comparison of various TES technologies, highlighting their advantages and limitations. A detailed

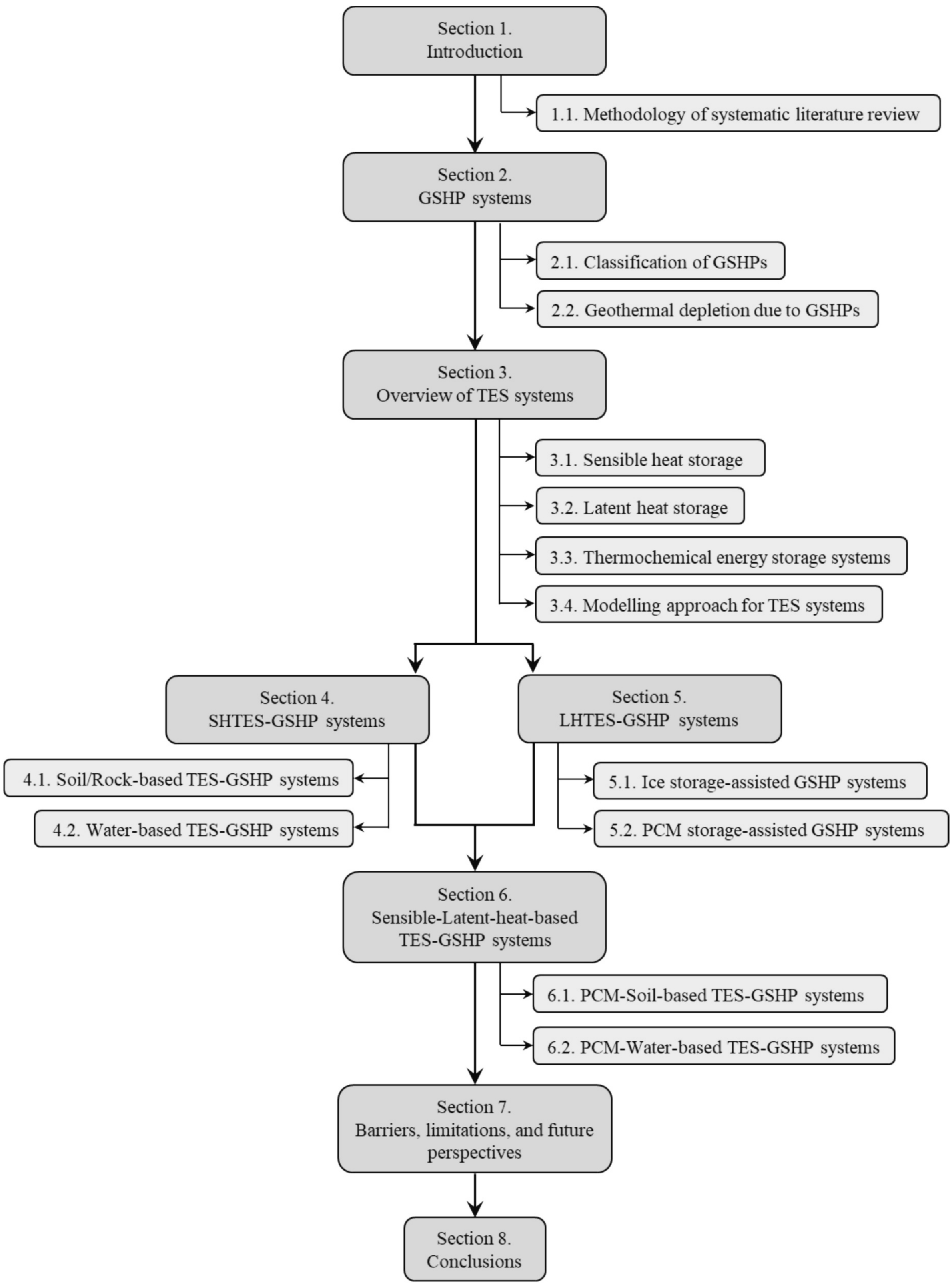

Fig. 1. Overall structure of the study.

analysis of each reference was conducted to compare various applications, configurations, modelling methodologies, and strategies to improve system performance. To aid the reader in quickly identifying the key attributes of the TES-assisted heat pump system investigated in each reference and relevant conclusions arising from the studies, a summarising table is included towards the end of each subsection within Sections 4-6. The outcomes of this review are expected to provide valuable insights for researchers and practitioners in the field of TES-assisted GSHPs and guide future research and development efforts in this area.

1.1. Methodology of systematic literature review

The methodology adopted in this paper for conducting the systematic literature review began by establishing a clear research question and objective, followed by the criteria for the inclusion or exclusion of references. The search strategy, data sources, screening process, data extraction, quality assessment, and data synthesis methods are detailed next to provide transparency in the adopted review process. Fig. 2 shows a flow diagram of the systematic process.

The objective of the literature review was to investigate the role of thermal stores in the performance of GSHP systems. The review was carried out to consolidate and categorise otherwise scattered research articles published with different short forms/acronyms for the same technology.

The search strategy adopted for curation of published articles was fairly simple yet effective. Relevant keywords such as "energy storage", "sensible heat storage", "latent heat storage", "ground heat exchanger", "ground-source heat pump", "geothermal heat pumps", "earth energy systems", and "ground-source systems" were used with different Boolean operators and filters to search the papers from different sources. Most of the relevant literature was collected from Web of Science, Scopus, IEEE, and Google Scholar.

The abstracts of the collected papers were assessed in the initial screening process. An exclusion criterion was employed for siphoning the papers that did not include TES-integrated energy systems and performance analysis of GSHPs, thus significantly reducing the number of collected papers.

The screened papers were then classified into three categories: a) sensible heat thermal energy storage (SHTES) integrated GSHP systems, b) latent heat thermal energy storage (LHTES) integrated GSHP systems, and c) hybrid TES integrated GSHP systems. Each paper was then thoroughly reviewed to extract data about the type of building thermal envelope studied, the considered climate conditions, type of study performed, the detail of energy system modelled, and the key findings of the reference. The papers missing these key aspects were excluded to ensure the quality of the review paper.

Fig. 3 shows the literature map of the selected papers considered for the systematic literature review of TES integrated GSHP systems. Each paper is represented by an orange circle. The links between two or more papers represent that one paper was cited by the other. The horizontal axis shows the year of publication while the vertical axis represents the number of times a paper has been cited. The majority of the papers included in this review were published within the last 5 years. This is evidenced by the dense cluster of dots on the right side of the map. It is important to highlight that the map does not depict all of the papers included in the review to maintain visual quality.

2. GSHP systems

GSHP systems utilise the ground thermal energy to provide heating and cooling for buildings, as well as hot water. These systems consist of three primary components: the ground connection subsystem, the heat pump subsystem, and the heat distribution subsystem [14].

2.1. Classification of GSHPs

The American Society of Heating, Refrigeration, and Air-conditioning Engineers (ASHRAE) has classified GSHP systems into three categories: ground water heat pump systems, surface water heat pump systems, and GCHP systems [28,29]. Fig. 4 shows the high-level schematic of different GSHP systems.

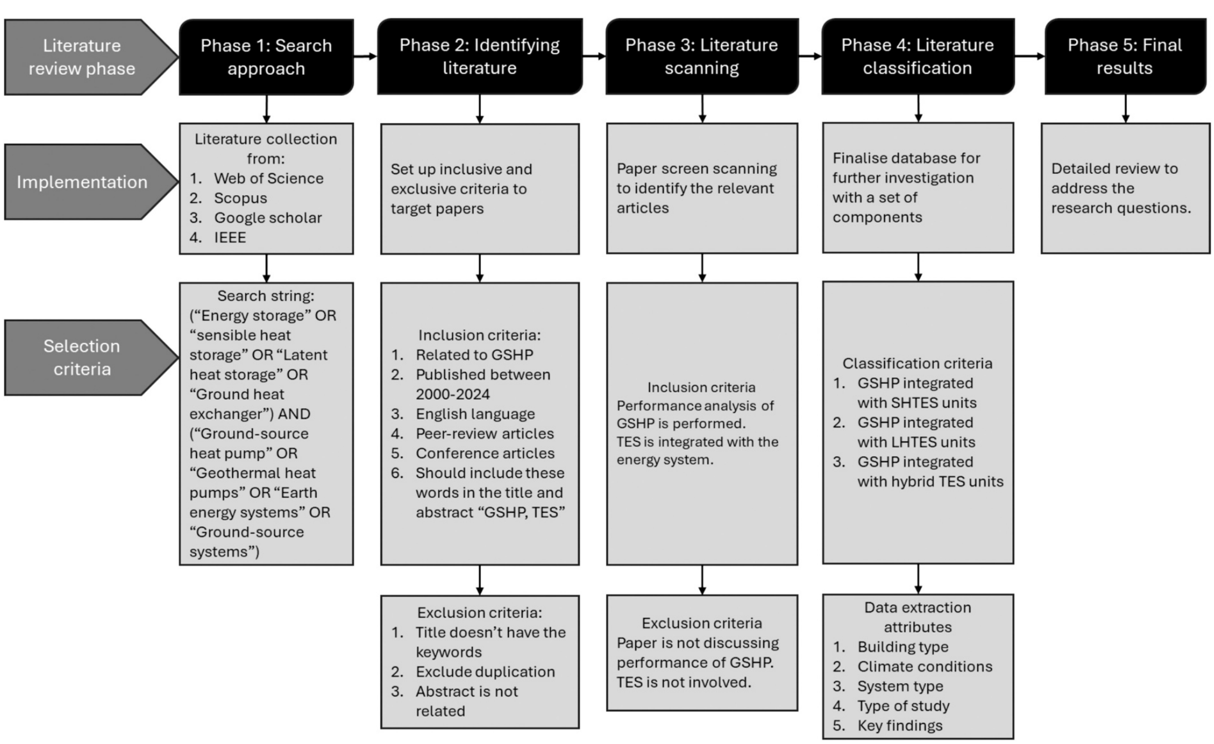

Fig. 2. Flow diagram for the systematic literature review process.

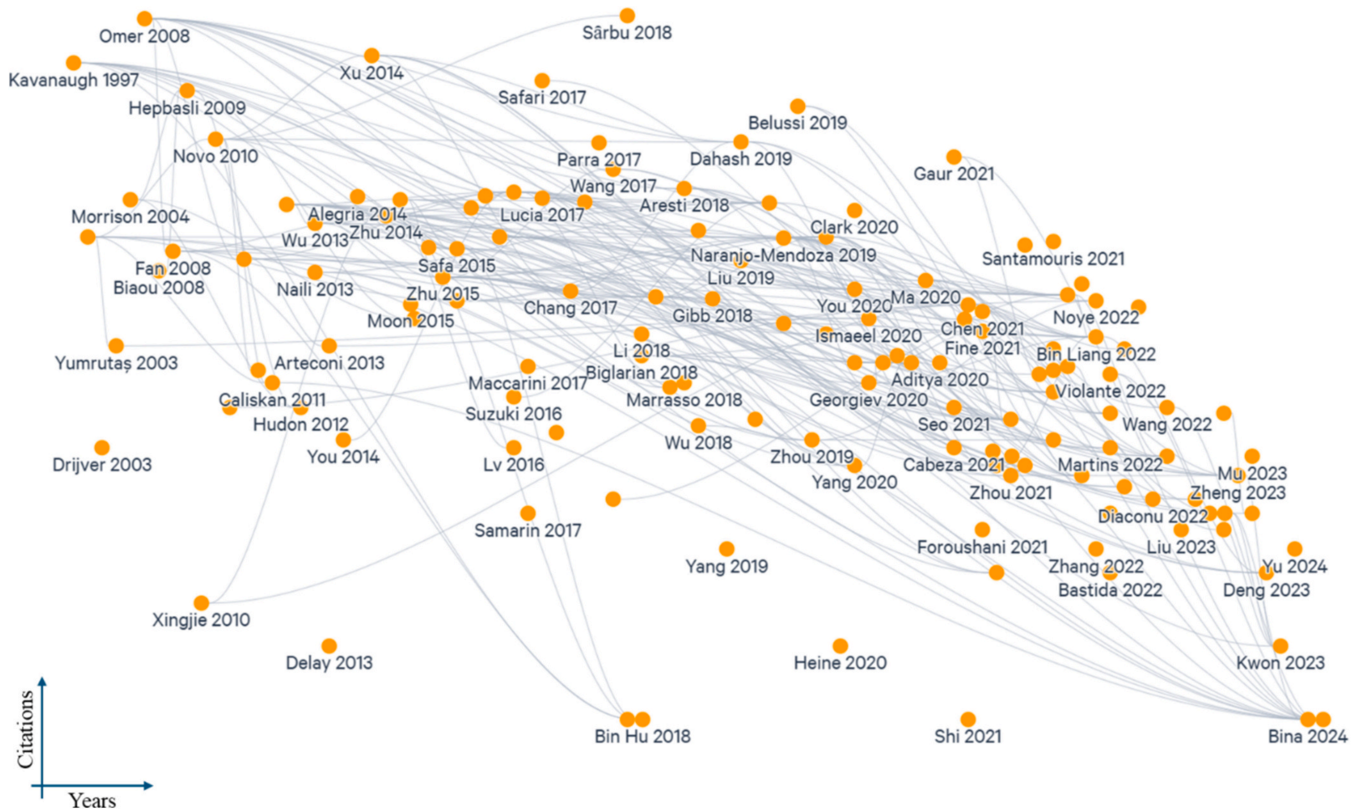

Fig. 3. Literature map.

Ground water heat pump systems utilise ground water as a heat source or heat sink, while surface water heat pump systems employ the heat stored in surface water bodies such as lakes, ponds, or reservoirs. In a closed-loop GCHP system, heat is exchanged between the working fluid and the ground through a closed-loop GHE. In turn, GHEs typically comprise thermoplastic pipes implanted in either horizontal trenches (horizontal borehole GHE) or vertical boreholes (vertical borehole ground heat exchanger, VBGHE) [13].

GSHPs have shown to be more economical compared to traditional systems in new construction projects, where they can be easily integrated to an outdated system or used altogether as a replacement, in climates with significant daily temperature variations or in regions with severe winter or summer temperatures and elevated electricity costs, and in locations where natural gas is not readily accessible or is more expensive than electricity [13].

2.2. Geothermal depletion due to GSHPs

Ground thermal imbalance occurs when the amount of heat extracted from or injected into the ground over time is not the same, leading to a gradual change in the ground temperature around a borehole [30]. This issue can be caused by imbalanced heating and cooling loads, where more heat is extracted or injected than the ground can naturally balance. Prolonged or continuous operation without periods of rest or sufficient thermal recharge of the ground can accelerate the onset of imbalance [31]. The thermal conductivity and heat capacity of the ground material play a crucial role; for instance, high conductivity can help dissipate heat more effectively, delaying imbalance. Due to this, systems in climates with significant seasonal temperature variations can face challenges in balancing heating and cooling loads [32].

The timeline for ground thermal decline or imbalance can vary from short-term to long-term durations depending on several factors. In systems with poor design or heavy, unbalanced loads, thermal imbalance may become noticeable within a few years (1-3 years). This might be seen in a reduced efficiency of GHEs or increased energy consumption of GSHPs to achieve the same heating or cooling effects prior to the imbalance [33].

Studies available in the literature indicate that notable thermal imbalance issues typically become more pronounced over a period of 3-10 years—especially in residential or small commercial configurations where the design of an energy system might not fully account for long-term operation [34]. For instance, a GCHP system for an office building in an extremely cold region with a total annual heating load of 818,228 kWh and cooling load of 192,351 kWh was analysed in [35]. The soil temperature and the borehole inlet and outlet temperatures showed a downward trend over a period of 10 years. In addition, the efficiency of the GCHP dropped sharply when the borehole medium temperature dropped below 0 °C. In another reference, a GCHP system of an office building in Harbin, China was simulated for 10 years to observe the hourly average soil temperature [36]. Utilising a GCHP for space heating decreased the soil temperature from 6.1 °C to −5.6 °C whereas if it was used for both space heating and space cooling the soil temperature dropped to −2.2 °C.

In general, continuous operation of a GCHP in heating mode drops the soil temperature significantly as heat is extracted from the soil without any heat injection; however, some heat recovery may be observed when the GCHP operates in cooling mode. In the long-term though, without proper management or adjustments, ground thermal imbalance may significantly affect system performance over a decade or afterwards [37], [30]. For instance, reference [38] reported that a 20-year operation of a single GCHP system in Beijing resulted in a soil temperature drop of 3.17 °C. This deterioration can lead in turn to substantial efficiency drops and might require costly interventions like drilling additional boreholes or installing supplementary equipment to improve system operation [39].

Various strategies have been investigated in the literature to mitigate ground thermal imbalance. For instance, the ground can be used to store excess heat in summer for use in winter and vice versa to balance the

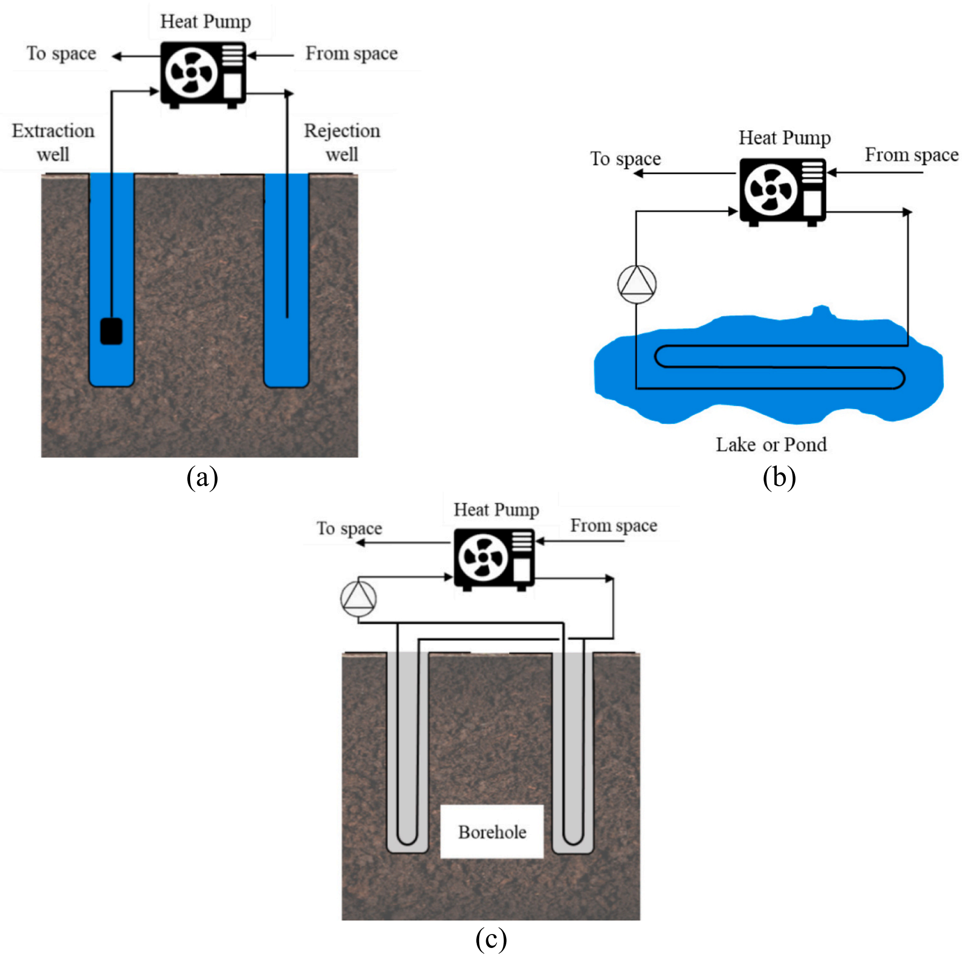

Fig. 4. Schematics of GSHPs: (a) ground water heat pump, (b) surface water heat pump, (c) GCHP.

thermal load [40]. Alternatively, thermal loads on the ground can be reduced by employing hybrid systems which combine geothermal systems with other heating/cooling methods [41]. System operation can be also modified to ensure balanced extraction and injection of heat and by actively managing the soil temperature through controlled thermal recharge [42]. For example, a transient simulation of a GSHP system in a hot-summer and cold-winter region was performed in [43]. It was reported that for an operation period of 20 years, the soil temperature increased by 0.34 °C with a heat recovery ratio of 53 % resulting in a ground thermal imbalance ratio of 5.2 %.

Other research work has reported that modifying GHEs can slow down thermal imbalance; however, an integrated GSHP system can significantly reduce the imbalance by increasing ground thermal injection and reducing thermal extraction [44]. This was demonstrated in [38], where the performance of a solar thermal collector-integrated GCHP was simulated for a continuous operation period of 20 years in climate conditions of Beijing, China. The yearly average space heating efficiency of the system was improved by 26.3 % without any drop in soil temperature compared to a conventional GCHP system. This was achieved by an improved utilisation of solar energy for space heating, heat storage, and soil thermal charging.

3. Overview of TES systems

TES systems possess the capacity to improve the efficiency of thermal energy equipment. They are particularly valuable in addressing the disparity between energy supply and demand. The complete process of energy storage involves three essential stages: charging, storage, and discharging. In practical applications, these stages may occur concurrently, and each stage can be repeated multiple times within a storage cycle. There are generally three types of TES systems: sensible, latent, and thermochemical [45–47]. A classification of the different energy storage materials for these systems is shown in Fig. 5.

3.1. Sensible heat storage

SHTES is a method of storing thermal energy by increasing the temperature of a storage medium without undergoing a phase change as shown in Fig. 6a. The amount of energy stored Q is determined by the specific heat c_p, temperature change ΔT, and mass m of the storage medium [48] using the following expression:

$$Q = \int_{T_i}^{T_f} mc_p dT = mc_p \left(T_f - T_i\right) \tag{1}$$

where T_i and T_f are the initial and final temperatures of the storage medium. Sensible heat storage is a simple and inexpensive method which does not involve the use of toxic materials. However, it requires a large volume of storage medium which is dependent on the amount of heat to be stored.

SHTES systems are classed based on the type of storage media used, which can be either liquid (water, oil, and molten salt) or solid (rocks and metals). Some commonly used storage materials include ceramics (cement and concrete), natural stones (clay, sandstone, marble, and granite), and polymers (PVC, PUR, and PS) [49,50].

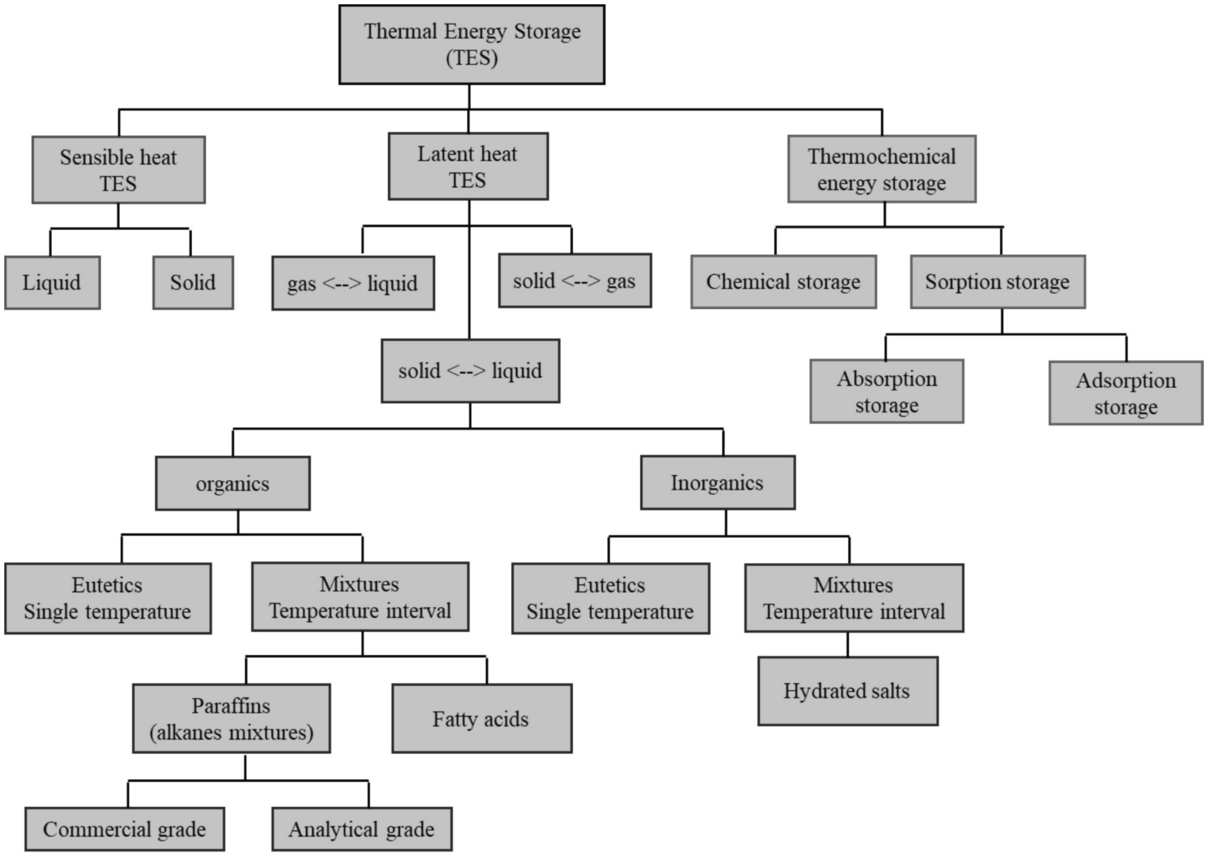

Fig. 5. Classification of energy storage materials.

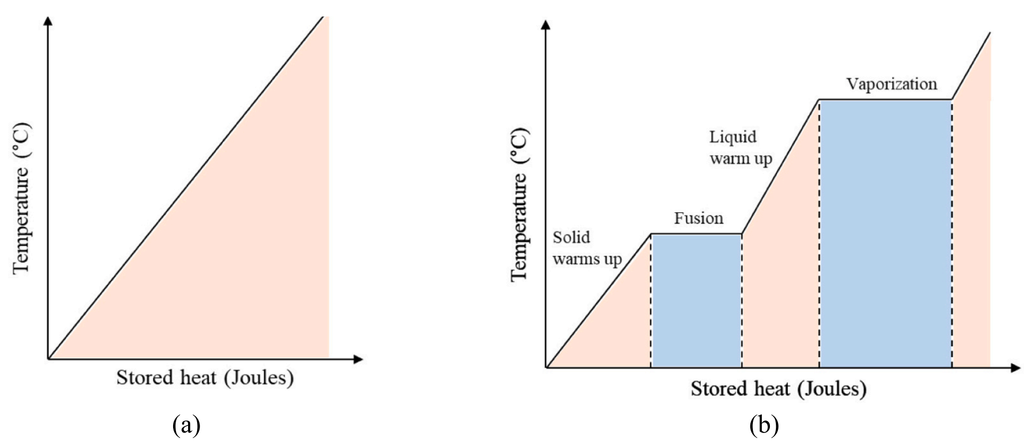

Fig. 6. Methods of TES: (a) SHTES, (b) LHTES.

3.2. Latent heat storage

The LHTES mechanism, also referred to as phase change material (PCM) storage, exploits substances with high specific latent heat to store and release heat energy during phase transitions. When a PCM reaches its phase change temperature, it absorbs a significant amount of heat, resulting in a change in its state, such as from solid to liquid or from liquid to gas. This absorbed energy is referred to as the latent heat of fusion or vaporisation. For example, as a solid PCM is heated, its temperature increases in proportion to the energy it receives until it reaches its melting point. Beyond this point, the energy is utilised to facilitate the phase transition, causing the material to change from a solid to a liquid state while maintaining an isothermal condition that preserves the thermal energy. Once the transformation is complete and the material is in the liquid state, its temperature continues to rise as it receives additional heat until it reaches the vaporisation point (see Fig. 6b). During the cooling process, the aforementioned phenomenon is reversed, allowing the stored energy to be extracted as latent heat at a constant temperature. This consistent temperature ensures that the released energy remains stable and can be effectively utilised for various applications [50].

It is important to note that while latent heat storage primarily stores energy as latent heat, some portion of the energy will also be stored as sensible heat during the temperature increase leading up to the phase change. The storage capacity of an LHTES system can be expressed by [48]:

$$Q = \int_{T_i}^{T_m} mc_p dT + ma_m \Delta h_m + \int_{T_m}^{T_f} mc_p dT = m\left[c_{ps}(T_m - T_i) + a_m \Delta h_m + c_{pl}(T_f - T_m)\right] \quad (2)$$

In the above expression, the first term signifies the sensible heat absorbed by the material due to its temperature rise from T_i (initial temperature) to T_m (phase change temperature). The second term corresponds to the latent heat stored by the material during its phase

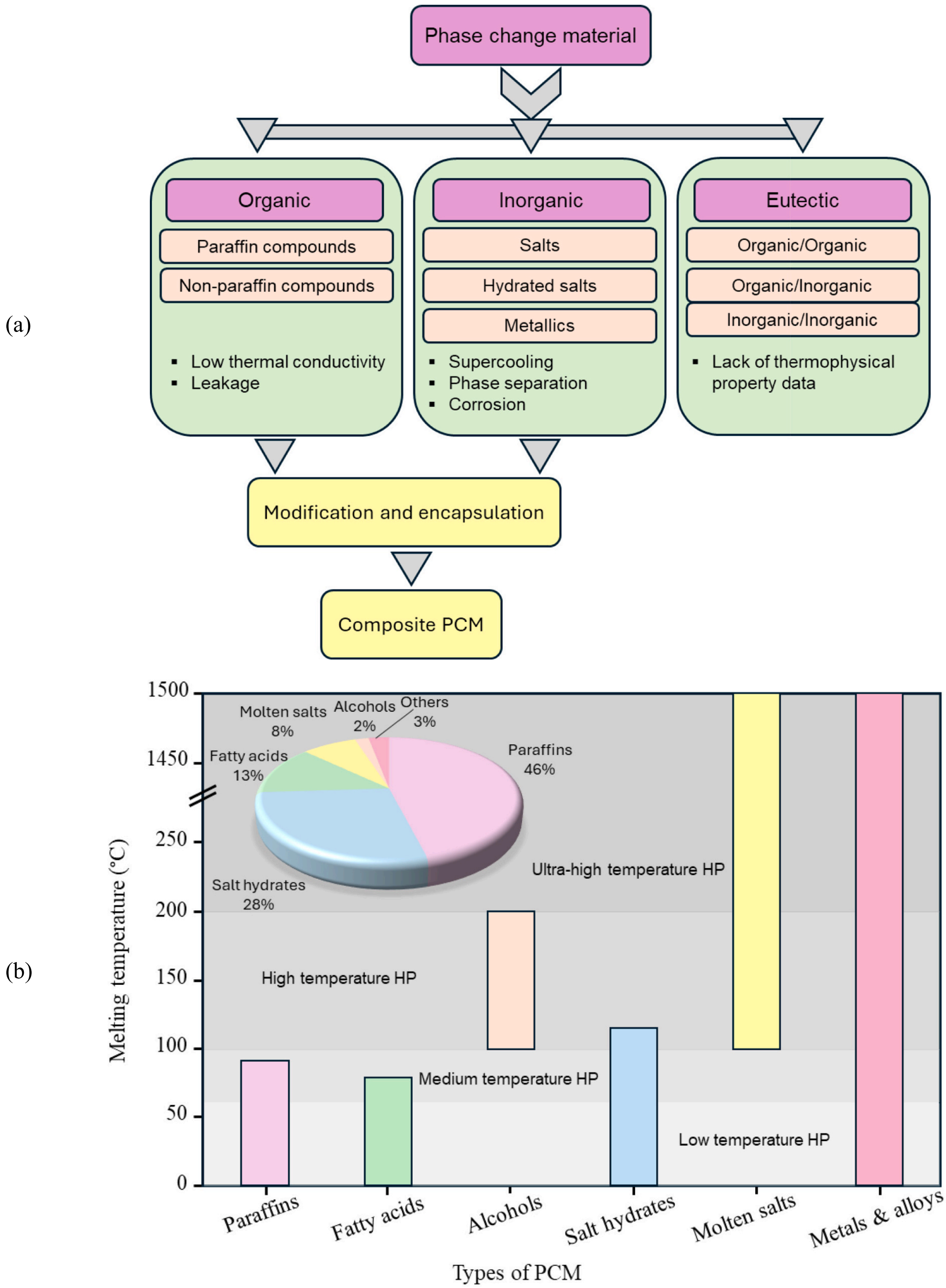

Fig. 7. (a) Classification of PCMs. (b) PCMs commonly integrated with heat pump systems. Content adapted from [61–63].

change, where a_m represents the melted fraction and Δh_m represents the heat of fusion per unit mass. The magnitude of energy stored depends upon the quantity of the material, the specific heat, and the concentration of the material that has undergone the transformation. A third term would appear in the equation to account for this additional sensible heat storage, in case the material is further heated beyond T_m to an arbitrary final temperature T_f. At the right-hand side of the equation, symbol c_{ps} refers to the specific heat of the PCM in solid phase whereas c_{pl} denotes its specific heat in the liquid phase [48].

PCMs are typically categorised into three main types: organic, inorganic, and eutectic, as illustrated in Fig. 7. Organic PCMs, such as paraffin, fatty acids, fatty alcohols, and sugar alcohols have a high latent heat capacity and a desirable phase change temperature but are characterised by low thermal conductivity and flammability [51]. Inorganic PCMs, such as salts, hydrated salts, and metals have high thermal conductivity, non-toxicity, non-flammability, and low cost, but can experience phase separation, subcooling, and corrosion. Eutectic PCMs, made of two different PCMs, exhibit high heat storage density without segregation during the phase change, but there is limited literature data on their thermophysical properties [52] and they may suffer from leakage during phase transitions. Composite PCMs are a new type of PCM with enhanced thermophysical and chemical properties to address the limitations of a traditional PCM. Composite PCMs integrate metal nanoparticles, carbon nanofibers, or carbon nanotubes into organic PCMs, or nucleating agents or thickening agents to inorganic PCMs [53]. The use of microcapsule encapsulation, high temperature-resistant ceramics, and composite materials with porous carbon-based materials can also help overcome corrosion and leakage exhibited by inorganic PCMs [54–57].

For application in heating and cooling systems, it is essential that the selected PCM or composite PCM has a suitable phase change temperature and a large latent heat, be non-toxic, non-hazardous, non-corrosive to the encapsulation material, and reusable. The newly developed composite PCMs have potential for use due to their appropriate melting points and favourable thermal properties, which can enhance user thermal comfort and meet the working parameters of the systems [58–61].

3.3. Thermochemical energy storage systems

There is another method of TES that utilises reversible endothermic chemical reactions. It exploits the use of chemical heat, which is the energy required to dissociate or break bonds in a chemical compound and that can be retrieved later during a synthesis reaction. Thermochemical energy storage systems are considered the most energy-efficient; however, they are still under development and have not yet been implemented in the building sector [64]. This technology faces significant challenges such as corrosion, poor heat and mass transfer performance, and more research is required to develop new composite materials with good cyclic ability and low price. Despite these challenges, the high energy density of the thermochemical processes and the absence of heat gains or losses during the energy storage make these systems suitable for seasonal storage applications [65].

The energy densities of the different TES systems previously discussed are presented in Fig. 8.

When designing a TES system, it is important to consider a variety of factors to ensure an optimal performance and a sustainable operation. Technical aspects, cost-efficiency, and environmental implications are key considerations that must be balanced in the design process [68]. The technical properties of the system include its thermal storage capacity, heat transfer rate, and material stability. A substantial thermal storage capacity has the potential to diminish system volume and enhance overall efficiency. Simultaneously, a proficient heat transfer rate between the heat storage material and heat transfer fluid facilitates the discharge or absorption of thermal energy at an optimal rate. The storage material must possess stability to mitigate the risk of chemical or mechanical degradation following a designated number of thermal cycles.

Cost-efficiency is another crucial aspect to consider, as it determines the payback period of the investment. The cost of a TES system typically considers three components: storage material, heat exchanger (HE), and land cost. An increased thermal storage capacity and improved heat

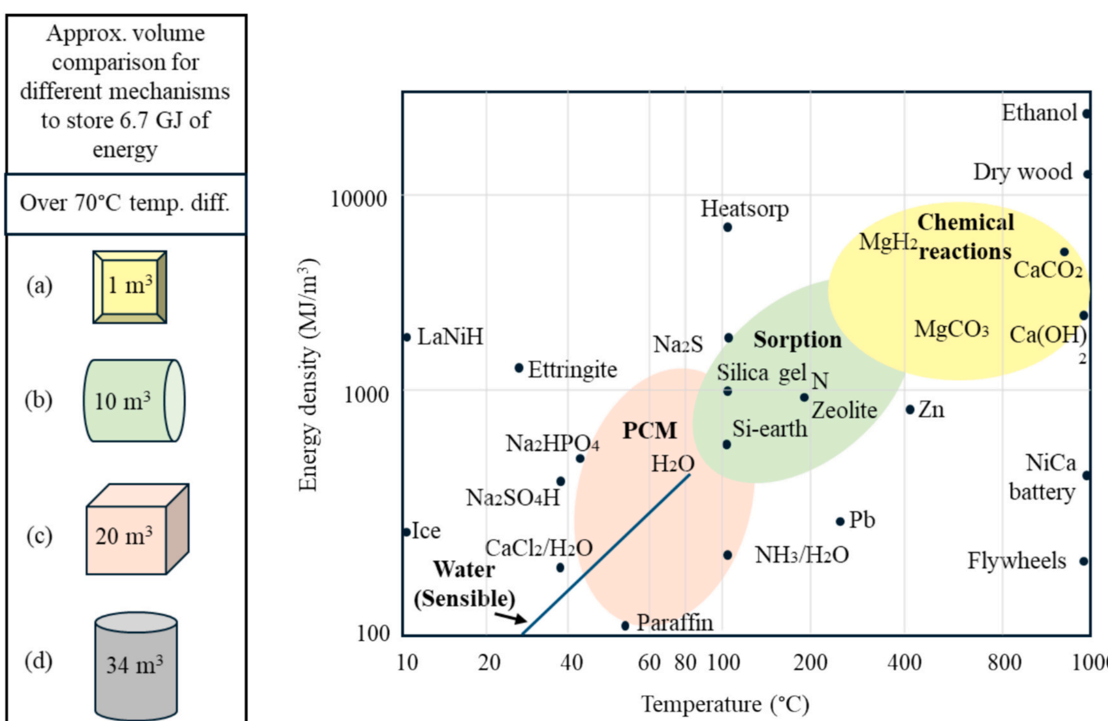

Fig. 8. Energy densities of different TES systems: (a) chemical reaction TES; (b) sorption TES; (c) LHTES; (d) SHTES. Diagrams adapted from [66,67].

transfer performance can substantially decrease the system's volume and ultimately decrease its overall cost. Environmental impact is also an important consideration, including factors such as the energy source used to charge the system, the materials used in construction, and the potential for emissions or other pollutants during operation. The system should be designed to minimise any negative impact on the environment and, in some cases, to even bring a positive impact by utilising renewable energy sources [69–71].

Other factors that need to be accounted for when designing a TES system include safety, reliability, and ease of maintenance. The system should be designed to meet all relevant safety regulations and standards and be reliable and easy to maintain to minimise downtime and ensure long-term performance. Additionally, the system should be easily integrated into existing energy infrastructure and be compatible with the specific energy source and application it is intended for. Overall, the design of a TES system requires a comprehensive approach that considers all relevant factors discussed in the previous paragraphs to ensure optimal performance and sustainable operation [69–71].

3.4. Modelling approach for TES systems

Theoretical models provide valuable insights into the expected performance of TES systems under various operating conditions. These mathematical models help in predicting system behaviour without the need for extensive empirical testing, thus saving time and resources [72]. Additionally, theoretical approaches may facilitate the optimisation of TES system design. By adjusting parameters within the models, optimal configurations and operational strategies that maximise efficiency and minimise costs can be identified [73]. A good model will also be helpful in understanding the underlying thermodynamic principles governing TES systems. This knowledge is crucial for advancing technology and improving existing designs. The models can be then scaled accordingly to evaluate systems of different sizes and capacities. This scalability is important for designing systems for various applications, which could range from residential to industrial settings [74].

Many models rely on simplifying assumptions to make the complex physics of TES systems more manageable. However, these assumptions can limit the accuracy of the models and may not fully capture a realistic behaviour. Particularly, the transient nature of heat transfer poses significant challenges for modelling. This is because accurately capturing the dynamic interactions within TES systems requires complex, time-dependent equations which are difficult to solve analytically. Moreover, model accuracy is highly dependent on the precise knowledge of the thermophysical properties of system components, as variations in thermal conductivity, specific heat, among other properties, can lead to discrepancies between theoretical predictions and actual performance [75]. Due to these issues, modelling the integration of TES systems with other components such as heat pumps or solar collectors is cumbersome. Component interaction can be complex and highly variable—thus further complicating the development of accurate models [76].

Modelling TES systems involves dealing with dynamic boundary conditions that change over time such as varying temperatures and heat fluxes. Capturing these dynamics accurately is challenging [74]. For instance, several TES systems use PCMs to store thermal energy. The phase change process involves non-linear heat transfer and latent heat effects, which are difficult to represent with a high degree of accuracy [76]. This is compounded by the often complex geometry of TES systems which affects heat transfer patterns. The models need to account for these geometries and doing so can be computationally intensive and analytically challenging [72]. Furthermore, high temporal resolution is required to accurately capture transient heat transfer processes. This increases the computational burden and complexity of the models, often requiring the use of numerical methods and simulations [77].

A detailed mathematical model for solving the equations describing a TES system typically involves a combination of heat transfer equations, thermodynamic principles, and material properties [78]. The primary equations governing TES systems involve energy balance and heat transfer principles. The energy stored in a TES system is described by the energy balance eq. [79]

$$Q_{in} - Q_{out} = \frac{dU}{dt} \tag{3}$$

where Q_{in} is the heat input to the system, Q_{out} is the heat output from the system, and dU/dt is the rate of change of internal energy.

Heat transfer in TES systems can be analysed through the fundamental heat conduction equation, which, in transient form, includes a time derivative term [79]. This is crucial for modelling and accounting how the system evolves over time. The transient heat conduction (diffusion) equation in one-dimensional form (along the x coordinate) is given by

$$\rho c_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2} \tag{4}$$

where t is the time and T, ρ, c_p and k are the temperature, density, specific heat capacity, and thermal conductivity of the heat transfer medium.

Eq. (4) shows that the rate of temperature change over time $\left(\frac{\partial T}{\partial t}\right)$ at any point in the material depends on the thermal diffusivity $\left(\alpha = \frac{k}{\rho c_p}\right)$ and the spatial second derivative of the temperature $\left(\frac{\partial^2 T}{\partial x^2}\right)$, which represents how temperature varies across space.

In systems where fluid movement is involved, heat transfer also occurs via convection [79]. Under these circumstances, the mass and momentum conservation equations are solved alongside the energy equation. The combined conduction-convection equation is expressed as [80]

$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p \overrightarrow{u} \bullet \nabla T = k \nabla^2 T \tag{5}$$

where $\overrightarrow{u}$ is the velocity vector of the fluid. This equation considers both the conductive and convective heat transfer mechanisms.

For systems using PCMs, the heat transfer includes both sensible and latent heat [81]. Thus,

$$Q = m c_p \Delta T + mL \tag{6}$$

where m is the mass of the PCM, ΔT is the change in temperature, and L is the latent heat of fusion.

The enthalpy of the material is calculated as the sum of the sensible enthalpy, h, and the latent heat, ΔH:

$$H = h + \Delta H \tag{7}$$

where

$$h = h_{ref} + \int_{T_{ref}}^{T} c_p dT \tag{8}$$

and h_{ref} is the reference enthalpy and T_{ref} is the reference temperature.

The liquid fraction, β, is defined as [81]

$$\beta = \begin{cases} 0, & T < T_{solidus} \\ 1, & T > T_{liquidus} \\ \dfrac{T - T_{solidus}}{T_{liquidus} - T_{solidus}}, & T_{solidus} < T < T_{liquidus} \end{cases} \tag{9}$$

The latent heat content ΔH is expressed in terms of the latent heat L of the material as

$$\Delta H = \beta L \tag{10}$$

The latent heat content may vary between zero (for a solid) and L (for a liquid).

For solidification/melting problems, the energy equation is written as

$$\frac{\partial}{\partial t}(\rho H) + \nabla \bullet (\rho \vec{u} H) = \nabla \bullet (k \nabla T) + S \quad (11)$$

where H is the enthalpy, $\vec{u}$ is the fluid velocity, and S is the source term.

The TES model must include boundary conditions to solve the heat transfer equations. These conditions could be:

- Dirichlet boundary condition, which specifies the temperature at the boundaries and is described by

$$T(0,t) = T_1$$

$$T(L,t) = T_2$$

- Neumann boundary condition, which specifies the heat flux at the boundaries, expressed as

$$-k\frac{\partial T(0,t)}{\partial x} = q_0$$

$$-k\frac{\partial T(L,t)}{\partial x} = q_L$$

- Robin boundary condition, which combines the previous two conditions, describing convective heat transfer at the boundaries, described by

$$-k\frac{\partial T(0,t)}{\partial x} = h(T_\infty - T(0,t))$$

$$-k\frac{\partial T(L,t)}{\partial x} = h(T(L,t) - T_\infty)$$

In the boundary conditions above, the temperatures and heat fluxes in the system boundaries are arbitrary as these are general expressions which do not represent any specific system.

Several numerical methods with varying fidelity are available and are suitable to solve TES integrated GSHP systems represented by the equations described in this section. For instance, white box solvers require a complete knowledge of the system's internal workings. The mathematical models and parameters are fully known and transparent. These solvers benefit from high accuracy and reliability. Detailed numerical models based on the finite difference method (FDM), finite volume method (FVM), and finite element method (FEM) are commonly used white box solvers. FDM is simple to implement; however it is less flexible for complex geometries and boundary conditions [82]. COMSOL Multiphysics [83] uses FEM for its simulations and it is well-suited for solving complex problems involving structural mechanics, heat transfer, and fluid dynamics. ANSYS Fluent [84] utilises FVM for fluid dynamics and heat transfer simulations. This approach involves dividing the computational domain into small control volumes and solving the mass, momentum, and energy governing equations for fluid flow and heat transfer within the control volumes. In general, white box solvers are suitable for detailed component-level analysis but are limited when it comes to system-level modelling.

In contrast, grey box solvers are based on semi-empirical models and simplified physical models with some empirical data. These solvers work with partial knowledge of the system where some parameters are known while other parameters are estimated or simplified. They provide a balance between accuracy and computational efficiency. Some common examples of software based on grey box solvers are MATLAB/Simulink [85], TRNSYS [86], Modelica [87], and EnergyPlus [88]. These solvers are less detailed compared to the white box solvers discussed in the previous paragraph. However, they offer a higher-level, modular approach where each component of the system (such as heat pumps, thermal storage, and building elements) is represented by a specific module. Such an approach makes it easier to undertake system-level simulations. Grey box solvers, in general, provide flexibility to model a wide range of systems including different combinations of integrated energy systems, heating ventilation and air conditioning systems, and building thermal envelopes.

On the other hand, black box solvers exhibit no knowledge of the internal workings of the system being modelled. They rely entirely on input-output data to model a system. They are particularly useful when the system is too complex to model or when detailed internal data is unavailable. The solvers often utilise machine learning models and neural networks. Common software example includes TensorFlow [89], which can develop models to predict the performance of TES-GSHP systems based on historical data and use reinforcement learning to optimise system operation to improve energy efficiency and cost savings. While black box solvers offer powerful capabilities for modelling complex systems, their limitations in transparency, data dependency, and computational complexity must be carefully considered when applying them to TES-integrated GSHP systems.

4. SHTES-GSHP systems

This section presents an overview of the recent advancements in the integration of SHTES systems with GSHPs. This includes soil and water-based storage methods, as well as rock and building fabric storage techniques. Given that there is limited research available on rock and building fabric storage, a short discussion on them is provided in the next paragraphs. The subsequent subsections instead consider a more comprehensive discussion on soil/rock and water-based storage systems.

Rock storage integration involves the utilisation of subsurface rock formations as heat sinks or heat sources for heating or cooling purposes through a GCHP system. This is achieved by circulating a heat transfer fluid through a network of pipes within the rock formations and the heat pump system. The rock formations employed can range from deep hard rock to shallow rock with high thermal conductivity and heat capacity, such as granite or basalt. In general, rock storage offers a larger storage capacity compared to soil and water storage with more stable temperatures [90]. However, it comes with challenges such as high installation costs, potential interference with underground infrastructure, and the need for detailed subsurface geology assessments [91,92].

Building fabric storage, as its name implies, involves storing thermal energy in the building fabric, like concrete walls and floors, to regulate indoor temperature and increase energy efficiency, resulting in cost savings [93].

4.1. Soil/rock-based TES-GSHP systems

TES integration may be achieved using moist soil as a medium to compensate for annual thermal imbalances and to recover soil temperature with minimal variations [94]. A sand and bentonite mixture is a prevalent grout material due to its exceptional ability to absorb water, its low permeability, and its capacity to expand and retain moisture. In this TES system, buried pipes serve a dual purpose as both thermal storage units and heat exchangers. During off-peak periods in summer or winter, heating or cooling energy is stored in the damp soil through these buried pipes and subsequently released to buildings during daylight hours. During transitional seasons, the buried pipes function as conventional GHEs [21].

Research has demonstrated that integrating soil storage with GSHPs can enhance the performance of heating and cooling systems by increasing the COP of the GSHPs and smoothing the load profile. Additionally, it allows for the utilisation of water at lower temperatures, reducing the size and cost of the HE [95]. Studies reported in references have also shown that soil storage can improve the performance of GSHPs in cold climates by raising the ground temperature at the beginning of the heating season, and by lessening the peak cooling load in hot climates through pre-cooling the soil before the cooling season [96]. However, several challenges arise, particularly in the design of the system, as it requires a thorough understanding of the thermal properties of the soil and the surrounding subsurface environment. Additionally, factors such as soil moisture content and subsurface water flow may affect system performance, which must be considered in the design process [97].

Naranjo-Mendoza et al. [94] performed an experimental study on a SAGSHP system with underground TES. The system utilised a shallow (1.5 m) VBGHE as a seasonal thermal store, known as earth energy bank. The overall schematic of the SAGSHP system is shown in Fig. 9. The system transferred heat from the solar system to a ground loop through a heat exchanger if temperature at the PVT collector outlet exceeded the soil temperature by 7 °C until the temperature difference became lower than 4 °C. On the contrary, the solar loop deactivated and the ground loop transferred heat from the VBGHE to the GSHP if the outlet temperature of the PVT collector became lower than the soil temperature. Results from a 19-month operation showed that the system effectively fulfilled the building's space heating requirements during winter. It also demonstrated the ability to inject 2.24 MWh of solar energy into the ground to meet the evaporator demand and maintain thermal balance. The results additionally indicated a need to improve the control strategy to prevent high fluid temperatures at the evaporator inlet.

Several references have analysed the use of soil storage in GSHP systems. Yu et al. [95] examined an integrated system with a cooling storage system in the soil. In the reference, a mathematical model to estimate the charging and discharging processes of the thermal store is presented and the model was validated with experimental results. Fan et al., in [98,99], proposed a dynamic mathematical model for a vertical dual-function GHE which takes into account the effects of heat conduction and groundwater advection on the heat transfer between the GHE and the soil. It was found that the GSHP-integrated system could achieve a high daily cold energy discharge, but groundwater impacted the heat transfer between the GHE and the soil, with different effects in summer and winter. Yang et al. [100] presented a soil-based cooling storage system using natural cooling from the ground to reduce energy consumption for summer air conditioning. The system used water as the working medium and showed to be efficient, cost-saving, and pollution-free. It was also shown that air conditioning needs could be met with the integrated system and, in addition, it had a good economic performance in a practical deployment in Harbin, China. Fan et al. [101] proposed an integrated HGSHP system with a cooling tower and a borehole cool energy storage system to improve cooling and heating in cooling load-dominated areas. A schematic of the integrated system is shown in Fig. 10. A diurnal cooling-injection and extraction method was adopted to optimise thermal performance. The results showed that the borehole cool energy storage system provided three times more cooling energy than a GHE without injection, improved the efficiency of the system, and reduced the peak power demand and the borehole area.

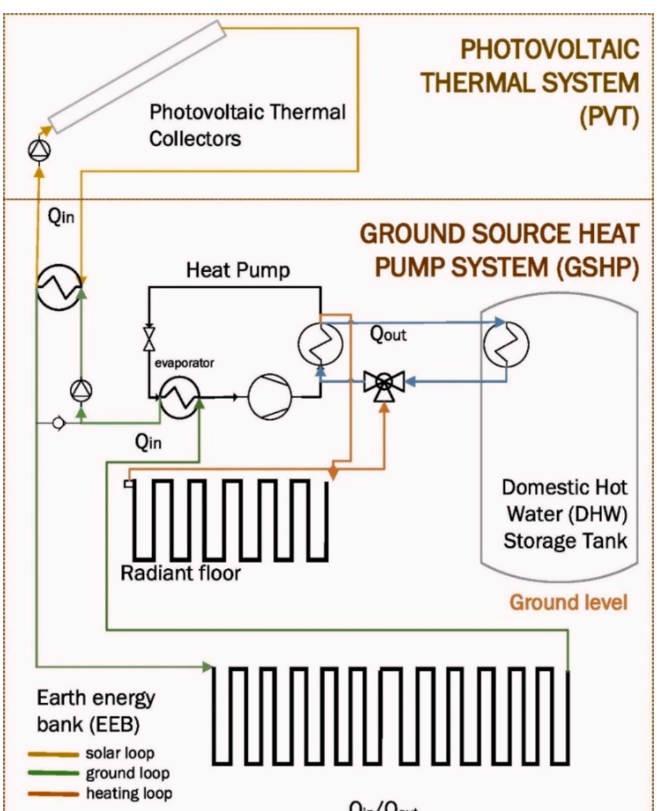

Fig. 9. Overall layout of the system configuration [94].

Zhou et al. [102] analysed the performance of a seasonal air-GCHP system using a seasonal borehole thermal energy storage (BTES) unit. The system was evaluated over 15 years and showed an improved performance in zones with copious solar energy. The optimal solar collector area was determined through a sensitivity analysis. Wang et al. [103] proposed a novel coupled-air and GSHP system with TES in a practical installation in Northern China to improve the operational cost of the GSHP. To this end, local electricity price profiles depending on the time of use for the duration of the study were adopted. The use of TES led to a 42 % reduction in operational cost and a 7.14 % reduction in carbon emissions, with a payback period of 3.16 years. Lv et al. [104] compared a GSHP system with a TES tank to a traditional GSHP system and reported that the TES-assisted system exhibited a better performance, incurred lower running costs, and required a lower initial investment, making it a promising solution. Shen et al. [105] developed an analytical model of soil-based TES systems and analysed the performance of the BHE by varying different design and operation parameters. The results reported a higher thermal conductivity of the backfill material, pipe diameter, and flow rate, leading to higher heat extraction capacity. The performance of soil-based TES integrated GSHP system under optimal flow rate resulted in 5.8 % reduction in electricity consumption.

Table 1 summarises the literature studies on soil/rock storage integrated GSHPs.

The literature studies demonstrate the potential of TES-integrated GSHP systems in achieving energy efficiency and sustainability goals—particularly in the residential and commercial building sectors. The current research is focused on improving the efficiency and effectiveness of soil-based TES systems by investigating the thermal properties of the soil and the surrounding subsurface environment. Researchers have examined the impact of varying soil moisture content on its thermal conductivity and effect of subsurface water flow on the heat transfer rate and thermal resistance in soil-based TES systems. Future research directions may involve incorporating advanced modelling techniques such as machine learning to optimise the performance of TES systems under various operating conditions. This may also include assessing the long-term environmental impacts and sustainability of soil-based TES systems.

4.2. Water-based TES-GSHP systems

Water is an attractive medium for energy storage due to its high specific heat capacity relative to other sensible heat-based storage media and its high charging and discharging rates [108]. Water-based systems include tank thermal energy storage (TTES), pit thermal energy storage (PTES), and aquifer thermal energy storage (ATES) systems.

A TTES system employs a stainless steel or reinforced concrete water tank as the storage medium, transferring heat to and from the tank by circulating a heat transfer fluid through a HE. The simplicity of design

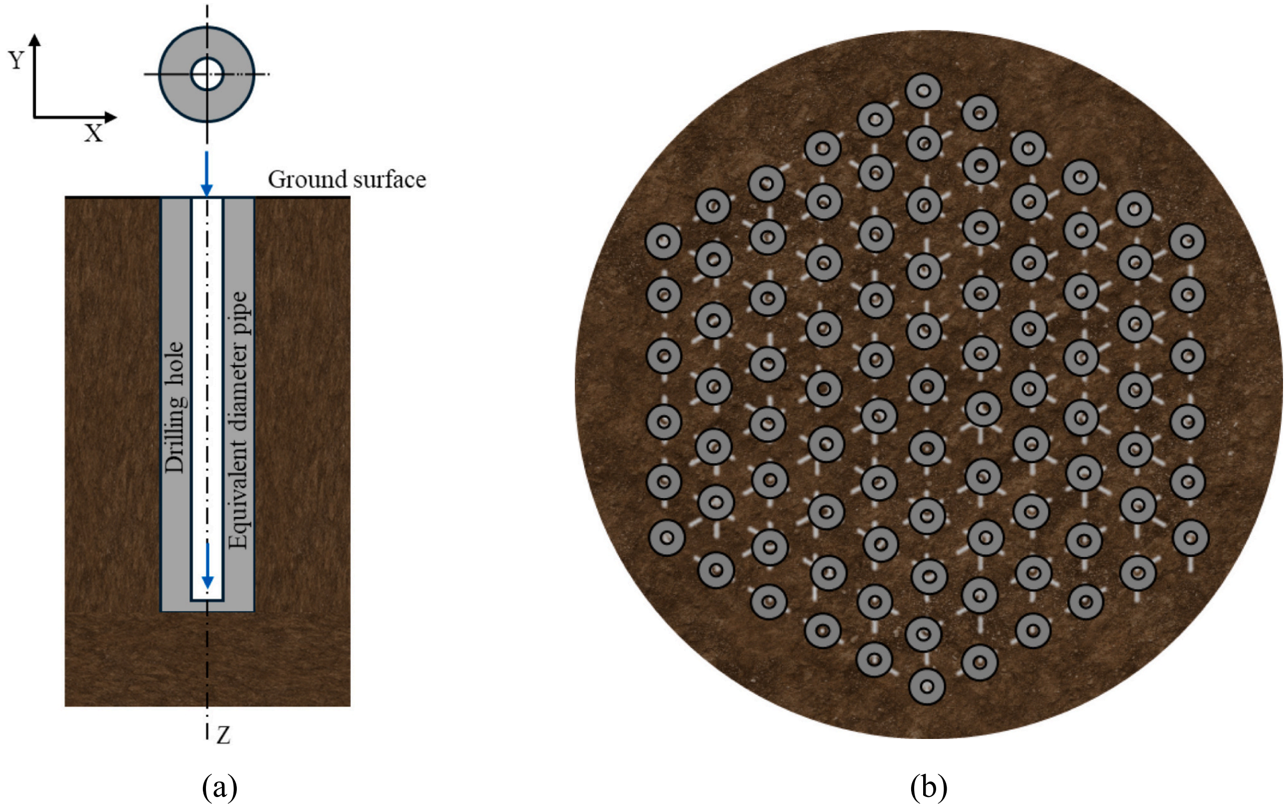

Fig. 10. (a) Schematic of the underground pipe. (b) borehole cool energy storage with 91 pipes at 1 m spacing. Schematics adapted from [101].

and construction makes TTES well-suited for projects with limited storage requirements [109]. PTES involves digging a pit into the ground and filling it with water, serving as both the heat storage medium and insulation. Heat is transferred to and from the pit by circulating a heat transfer fluid through a HE [110]. TTES and PTES systems operate in a stratified manner, with hot water located at the top and colder water placed at the bottom. Schematics of TTES and PTES units are shown in Fig. 11.

ATES units utilise an underground aquifer as the heat storage medium, transferring heat to and from the aquifer via wells (shown in Fig. 12) [112]. The high volume of water in the aquifer provides a large storage capacity, while the underground location stabilises the stored heat, leading to an improved efficiency. Heat is transferred to and from the aquifer through thermal wells, in which one is designated for hot water and the other for cold water. Groundwater serves as the heat transfer fluid and the porous aquifer allows for storage of thermal energy. During the charging process, cold groundwater is pumped and heated by a GSHP before being introduced into the hot-well. In the discharging process, the flow is reversed [113,114].

There has been a growing interest in using water storage systems to enhance the performance of GSHP systems. Gan et al. [115] conducted a study on a unique rainwater-GSHP integrated system. The system was based in Nottingham, United Kingdom, and included a heat pump, water and soil storage tanks, and HEs, which were tested under controlled conditions. The study found that a HE is necessary for heat exchange between the rainwater and the soil for the effective operations of the GSHP system over a long period of time. The study also suggested that the performance of the rainwater-GSHP system is dependent on the factors such as the mode of operation, the load, and type and size of HE used. The use of heat pipes as a replacement for solid HEs was also considered as shown in Fig. 13, but the external resistances may hinder the heat transfer particularly in the restricted space of the water tank. Given the challenges imposed by the impure and corrosive nature of rainwater, the required investment for the integrated system, its complexity, and maintenance (e.g. cleaning the tank) were assessed.

Yu et al. [116] evaluated the performance of a GSHP system integrated with an adit water source for an office building (6800 m^2) in Jinzhou, China. Numerical simulation was employed to analyse the feasibility of the GSHP system and provide data for engineering design. The presented results confirmed an adequate system behaviour, with the measured adit water temperature matching the predictions. The use of water storage in GSHP systems allowed for consistent year round cooling and heating, with the energy efficiency of the system dependent on water quality, temperature, and maintenance of the water tank.

Yumrutaş and Ünsal [117] determined the annual performance of a SAGSHP space heating system with seasonal TES using an analytical and a computational model. Results showed that earth type affects the annual energy fractions, the thermal storage transient temperature, and COP of the heat pump. Lower thermal conductivity earths yielded a better system performance. The study also found that the storage radius only showed gains beyond 25 m and that increasing the burial depth beyond 1 m had a small effect on the annual performance. The results indicated the feasibility of seasonal energy storage in surface tanks with shallow burial depths. Yumrutaş et al. [118] investigated the annual performance of a SAGSHP system with an underground TES unit. It was found that the heating system was technically feasible, with the earth type and system size having a significant effect on performance. The highest storage temperatures occurred when coarse gravel was used and the lowest when granite was adopted instead. The amplitude of the storage temperature increased when the storage size was decreased, and the earth surrounding the storage acted as an additional energy storage medium.

Rostampour et al. [119] developed a nonlinear model predictive control framework for the heating and cooling system of a building. The model considers the building thermal dynamics, the dynamics of the ATES system, a GSHP with a HE, and water pipelines. The results demonstrated a good system performance. However, a trade-off between model complexity and simulation time is necessary to assess the

Table 1
Summary of the literature studies on soil/rock storage integrated GSHPs.

Authors and reference	Type of building / facility	Country and year	Climate conditions [106]	Type of system	HP modelled	Type of study	Major findings
Yu et al. [95]	Test facility	Nanjing, China, 2008	Cfa (temperate, no dry season, hot summer)	Soil storage-based GSHPs	No	Experimental and numerical	Formulated a mathematical model to estimate the process of charging and discharging.
Fan et al. (2008) and Fan et al. (2007) [98,99]	Office building	Shanghai, China, 2007	Cfa (temperate, no dry season, hot summer)	Soil storage-based GSHPs	Yes	Numerical	Daily energy discharge efficiency of 89 % without groundwater flow and 71 % with groundwater flow.
Yang et al. [107]	Test facility	Harbin, China, 2012-2013	Dwa (continental, dry winter, hot summer)	Soil storage-based hybrid GCHPs systems with cooling tower	No	Experimental and numerical	System COP ranged from 7.90 - 13.32.
Fan et al. [101]	Test facility	Shanghai, China, 2015	Cfa (temperate, no dry season, hot summer)	Soil storage-based GCHPs	No	Numerical	The system provided up to 89 % of the cooling load requirement.
Naranjo-Mendoza et al. [94]	Residential building	Leicester, UK, 2016-2017	Cfb (temperate, no dry season, warm summer)	Soil storage-based solar assisted GSHPs	Yes	Experimental	An average monthly seasonal performance factor of 2.51 was recorded.
Zhou et al. [102]	College campus building	Changsha, Guangzhou, Kunming, China, 2021	Cfa (temperate, no dry season, hot summer) for Changsha and Guangzhou, Cwb (temperate, dry winter, warm summer) for Kunming	Soil storage-based solar-assisted GCHP	Yes	Numerical	Proposed system had a seasonal performance factor of 2.78, 3.00, and 4.76 in Changsha, Guangzhou, and Kunming, respectively, with higher values in areas with abundant solar energy resources.
Wang et al. [103]	Hotel building	Zibo City, China, 2022	Cwa (temperate, dry winter, hot summer)	Soil storage-based coupled air and GSHP	Yes	Numerical	System COP = 2.3, Optimising the defrosting control increased heating capacity by 13.9 % and reduced operating cost by 58 % and carbon emissions by 7.14 %.
Lv et al. [104]	Office building	Tianjin, China, 2016	BSk (dry, semi-arid steppe, cold), bordering Dwa (continental, dry winter, hot summer)	Soil storage-based GSHP	Yes	Experimental and numerical	Integrated TES-GSHP system exhibited higher COP compared to a conventional GSHP by 0.37 in winter and 0.04 in summer.
Shen et al. [105]	Residential building	Beijing, China, 2023	Dwa (continental, dry winter, hot summer), bordering BSk (dry, semi-arid steppe, cold)	Soil storage-based GSHP	Yes	Analytical	The optimal BHE design factor values led to reduction in electricity consumed by the GSHP system (from 5110 kWh to 4812 kWh).

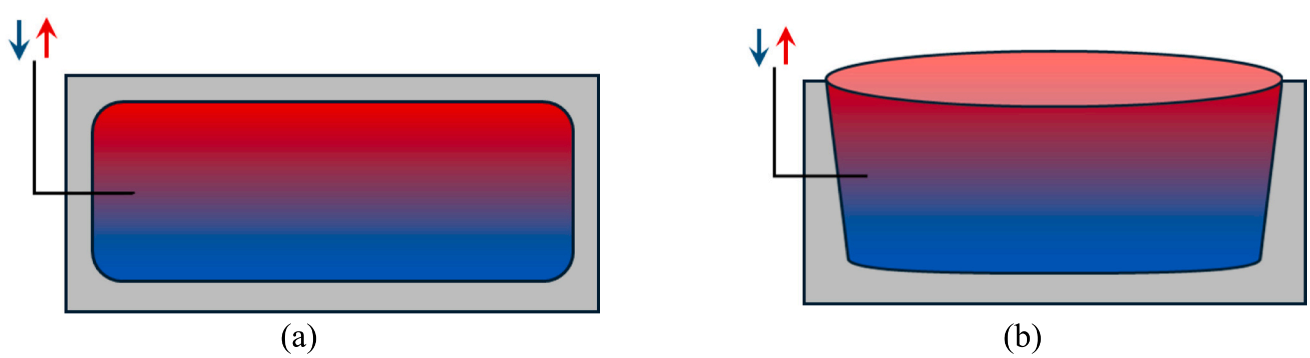

Fig. 11. Schematic of water-based TES systems [111]: (a) TTES, (b) PTES.

performance of the ATES system. The study by Ismael and Yumrutaş [120] presented a mathematical model of a wheat drying system with a GCHP and a TES tank charged by solar energy. The performance parameters were analysed using analytical solutions and a MATLAB program. The results showed that the system performance improves in the first five years and operates periodically thereafter, with the earth type and geological structure having a significant impact on performance. The optimal configuration included a collector area of 70 m^2, a TES tank volume of 200 m^3, and a wheat mass flow rate of 50 kg/h with 40 % Carnot efficiency, resulting in a heat pump COP of 4.43, a system COP of 4.3, and specific moisture evaporation rate of 6.05. Solar energy provided 76.6 % of the total energy input, while compressor work provided 22.7 % and fan power 0.7 %.

Qian et al. [121] investigated the cost effectiveness of a HGSHP system integrated with TES. The HGSHP system adopted a less expensive heat sink (or heat source) to reduce the size of the more expensive GHEs. The system integration allowed for a full utilisation of the available heating and cooling output even when the GSHP was not running and helped balance the annual heating and cooling loads of a building. A preliminary simulation study was conducted using a Modelica program to evaluate the integrated system in a heating-dominant residential building in Chicago. The results demonstrated that the efficiency of the GSHP was enhanced (or the size of GHE reduced) while maintaining the same energy efficiency as with a conventional GSHP system.

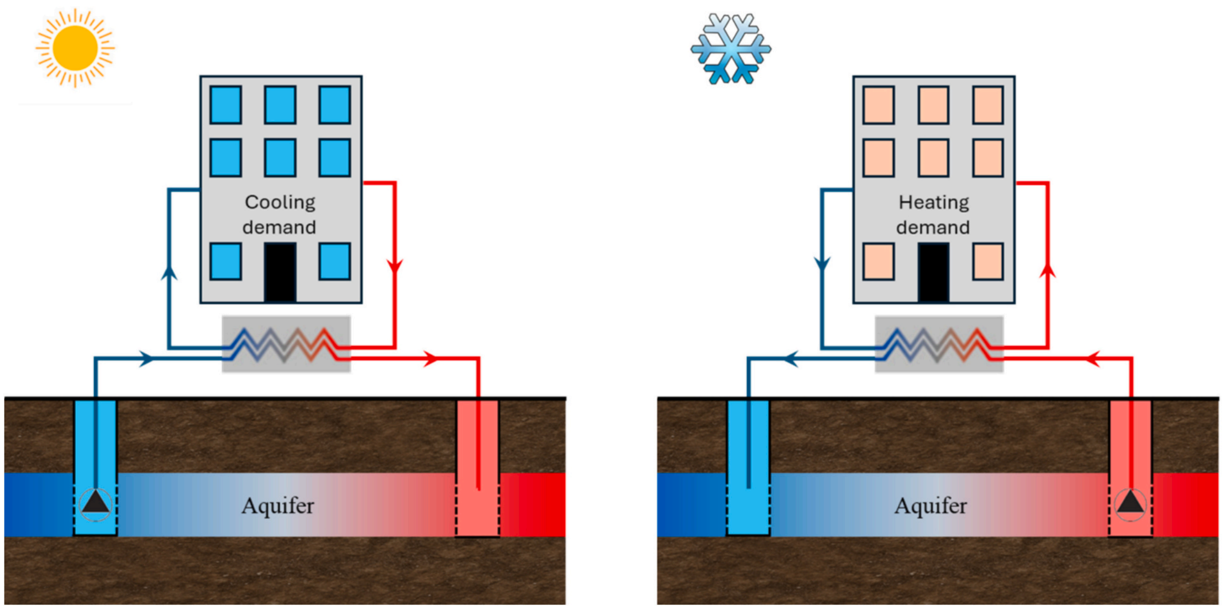

Fig. 12. Schematic of an ATES system (adapted from [112]).

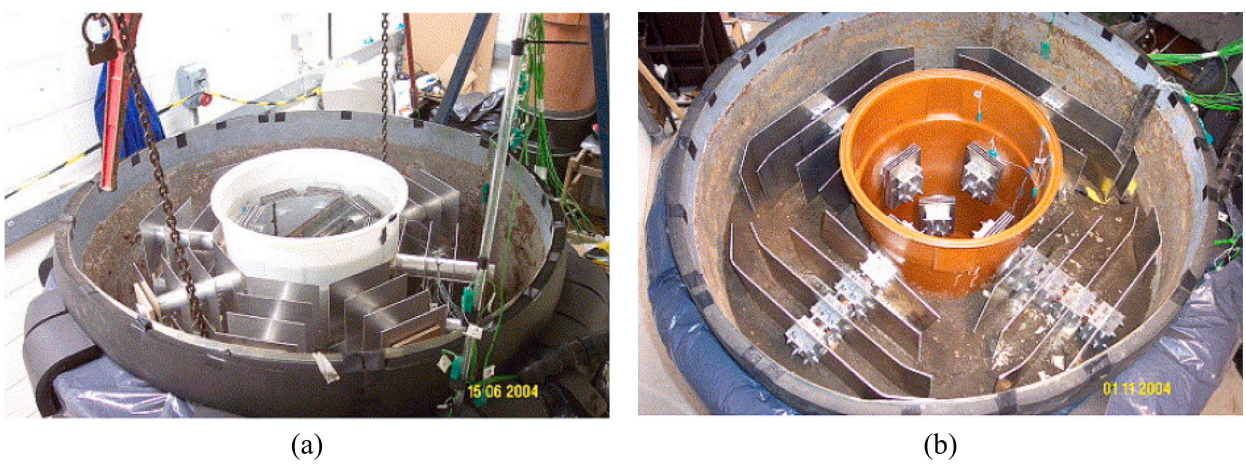

Fig. 13. HE in soil and water tanks: (a) Solid bar HE and (b) heat pipe HE investigated by [115].

Integration of GCHPs with TES systems has been also investigated in the literature. For instance, Caliskan et al. [122] investigated the system energy, exergy, and sustainability for different reference temperatures in a TES-integrated solar-GCHP system. The findings indicated that an exergy analysis proved to be more valuable compared to an energy analysis considering the system efficiency and performance. The performance of the TES system depended on the solar radiation, the volume of the water storage, and the size of the solar collector, with a maximum exergy efficiency of 40.99 %. The maximum heat loss occurred in the solar collectors. In a study by Zhu et al. [123], the impact of a solar seasonal storage integrated with a GSHP system on the operational efficiency of the system and the heat pump unit was investigated. The COP was estimated before and after the solar seasonal storage experiment and compared. The findings showed that the average soil temperature improved by 0.21 °C after the experiment, and the COP of the GSHP system increased by 3.4 % to 3.07, while the COP of the heat pump unit increased by 2.4 % to 4.22. In addition to improving the COPs, the study also concluded that the utilisation of solar seasonal storage integrated GSHP system might be a better option considering financial and environmental aspects compared to other systems such as urban heating and gas-boiler systems.

Different combination of heat pumps along with TES units have been investigated to determine the most energy efficient solution. Pardo et al. [124] found that using a TES system and combining a GCHP with an air-to-water heat pump improved the energy efficiency in a cooling-dominated office building located at the Mediterranean coast. This combination of two heat pumps and a TES device achieved the highest cooling performance, reducing the electrical energy consumption by 60 % compared to an air-to-water heat pump and by 82 % compared to GCHP configuration when used separately. The combined configuration also had the best pay-back period and cost efficiency. The reference suggested that similar results are achievable in other buildings exhibiting with similar characteristics under comparable environmental conditions.

Integration of BTES-assisted heat pump technologies with renewable energy sources has also been a subject of investigation. In [125], a hybrid thermal system with a GSHP and solar collectors tested under different operational modes was studied. The results showed that the intensity of solar radiation on the solar collectors was higher than normal due to the large roof panel acting as a non-imaging concentrator. The temperatures in the two water reservoirs were similar, making them usable as a single storage tank. The ground temperature increased during the charging of the BTES unit with solar collectors and decreased during the GSHP heating mode, emphasising the importance of charging the BHE with thermal energy from the sun. The energy efficiencies of the three heating modes were 48.59 % for direct solar heating, 96.46 % for a GSHP heating mode, and 97.95 % for solar assisted heat pump heating, with the GSHP heating mode having the highest efficiency and being the most advantageous over the other two modes.

Zheng et al. [126] proposed a graded TES-integrated SAGSHP to utilise otherwise wasted weak solar radiation and reduce soil thermal imbalance associated with a conventional SAGSHP system. Two water tanks were utilised: a load water tank for domestic hot water provision and a storage water tank to store heat. The graded utilisation of solar energy was established by connecting a solar collector with the load tank, storage tank, and a BHE individually according to the intensity of solar radiation. The proposed system showed a high solar collector thermal efficiency of 42.7 % whereas, the conventional SAGSHP system had an efficiency of 19.4 %.

Chang et al. [127] proposed a PVT curtain wall coupled with a water-based thermal energy storage-dual source heat pump (TES-DSHP). The curtain wall was connected with the air-source side of a DSHP and covered the south façade of the building. The seasonal coefficient of performance (SCOP) of the proposed system showed a 6 % increase compared to that from an energy system without the PVT curtain. Moreover, for the same energy consumption, the proposed system needed only half as many drilled wells required by a conventional DSHP system.

Table 2
Summary of the literature studies on water storage-integrated GSHPs.

Authors and reference	Type of building / facility	Country and year	Climate conditions [106]	Type of system	HP modelled	Type of study	Major findings
Gan et al. [115]	Test facility	Nottingham, UK, 2005	Cfb (temperate, no dry season, warm summer)	Rainwater storage (tank)- based GSHP	No	Experimental and numerical	The size of the system HE depends on the operation period and load.
Yu et al. [116]	Office building	Jinzhou, China, 2006	Dwa (continental, dry winter, hot summer)	Adit water storage based GSHP	Yes	Experimental and numerical	Average COP (winter) = 4.4, Average COP (summer) = 6.0
Yumrutaş and Ünsal [130]	100 residential buildings	Gaziantep, Turkey, 2000	Csa (temperate, dry summer, hot summer)	Water storage (tank)-based solar GCHP	Yes	Analytical and numerical	High storage tank transient temperature and the annual COP
Yumrutaş et al. [118]	Residential Building	Isparta, Turkey, 2003	Csa (temperate, dry summer, hot summer)	Water storage (tank)-based GCHP	Yes	Analytical and numerical	The highest COP was achieved with storage embedded in coarse gravel earth, while the lowest COP was observed in granite
Rostampour et al. [119]	Building with a single zone and wall layers.	Delft, the Netherlands 2017	Cfb (temperate, no dry season, warm summer)	Water storage (aquifer) -based GSHP	Yes	Analytical	A nonlinear model predictive control framework was used to simulate the heating and cooling system of a building, showing a good performance with a trade-off between model complexity and simulation time.
Ismaeel and Yumrutaş [131]	Wheat drying system	Gaziantep, Turkey, 2020	Csa (temperate, dry summer, hot summer)	Water storage (pit)-based GSHP	Yes	Analytical	Heat pump COP = 4.43. System COP = 4.3 Specific moisture evaporation rate (SMER) = 6.05
Qian et al. [121]	Heating dominant residential building	Chicago, IL, USA, 2020	Dfa (continental, no dry season, hot summer)	Water storage (tank)-based GSHP	Yes	Numerical	Integration of water storage tank in the system enhanced GSHP's efficiency or allowed downsizing while maintaining energy efficiency.
Caliskan et al. [132]	Residential building	Tianjin, China, 2011	BSk (dry, semi-arid steppe, cold), bordering Dwa (continental, dry winter, hot summer)	Water storage (pit)-based SAGSHP	Yes	Analytical	Max. exergy efficiency = 40.99 % Max. energy efficiency (42.94 %) at a reference temperature of 0 °C.
Zhu et al. [123]	Educational building	Tianjin, China, 2015	BSk (dry, semi-arid steppe, cold), bordering Dwa (continental, dry winter, hot summer)	Water storage (tank)-based SAGSHP	Yes	Experimental	Heat pump COP increment = 3.4 % System COP increment = 2.4 %
Pardo et al. [124]	Office building	Valencia, Spain, 2010	BSk (dry, semi-arid steppe, cold)	Water storage (tank)-based hybrid GCHP and air-source heat pump	Yes	Numerical	The hybrid configuration achieved the highest efficiency improvement with cooling mode performance factor of 3.8
Georgiev et al. [125]	Educational building	Plovdiv, Bulgaria, 2020	Cfa (temperate, no dry season, hot summer)	Water storage (tank)-based SAGSHP	Yes	Experimental	Charging the BHE with solar thermal energy and using GSHP heating are crucial to prevent ground thermal depletion
Zheng et al. [126]	Campus dormitory	Changsha, China, 2023	Cfa (temperate, no dry season, hot summer)	Graded water storage (tank)-based SAGSHP	No	Numerical	The proposed graded water storage (tank)-based SAGSHP resulted in solar collector thermal efficiency of 42.7 %.
Chang et al. [127]	Residential building	Shenyang, China, 2023	Dwa (continental, dry winter, hot summer)	Water storage (tank)-based PVT-DSHP (air+ground)	Yes	Experimental and numerical	Addition of PVT curtain wall improved the SCOP of the DSHP from 3.1 to 3.3.
Kwon et al. [128]	Residential building	Incheon, South Korea, 2023	Cwa (temperate, dry winter, hot summer), bordering Dwa (continental, dry winter, hot summer)	Water storage (tank)-based GSHP	Yes	Numerical	The water storage tank integrated GSHP system reduced the CO_2 emissions by 49 %.
Yu et al. [129]	Residential building	Shenyang, China, 2024	Dwa (continental, dry winter, hot summer)	Water storage (tank)-based SAGSHP	Yes	Numerical	The applied demand management strategy showed an energy saving potential of 41.8 %.

Kwon et al. [128] performed a numerical study to investigate the performance of a hot water tank-integrated GSHP system. Several cases were simulated to evaluate the effect of different design factors such as water tank volume, tank setpoint temperatures, and GHE on the GSHP unit. As suggested by the results, the performance of the GSHP system increased by 12.6 % based on design factors. Moreover, compared to a district heating system, although the investment cost of different GSHP systems based on different design factor combinations was higher by 51.5-84.7 %, however, annual operation costs were 20.8-33.1 % lower. In a numerical study, Yu et al. [129] combined a PVT system with the water-based TES-GSHP and coupled it with demand-side management model to achieve optimal balance between energy production and power-load on the grid. The applied demand management strategy showed an energy saving potential of 41.8 %. The coupled energy system showed a lower energy consumption compared to stand-alone GSHP system. The annual cost of electricity was reduced by 58.9 %.

A summary of the literature studies on the water storage-integrated GSHPs is presented in Table 2.

Overall, water-based TES integrated GSHP systems offer substantial benefits in terms of efficiency and decarbonisation. However, challenges related to model accuracy, insulation, and system complexity need to be addressed to fully realise their potential. Advanced control schemes such as those based on model predictive control, which integrate dynamic models of building envelopes and HVAC systems, may be conducive to improve operational efficiency and responsiveness to energy demand. Having said that, care should be exercised when adopting such control schemes as their effectiveness is heavily dependent on the accuracy of the predictive models and inaccurate predictions can instead reduce system performance. Developing and integrating advanced control strategies and hybrid systems may also increase complexity and initial costs, which could be a barrier preventing widespread adoption.

5. LHTES-GSHP systems

This section summarises the recent progress in the integration of LHTES with GSHP systems. The TES-GSHP systems discussed include ice and PCM-based systems.

5.1. Ice storage-assisted GSHP systems

Ice storage, a form of latent heat storage, can be integrated with a GSHP system to provide an efficient and cost-effective method for heating and cooling buildings. The basic principle of ice storage involves freezing water into ice during off-peak hours, when electricity is cheaper and in surplus, and subsequently utilising the stored ice to provide cooling during peak demand periods [133].

A typical ice storage system comprises three components: a refrigeration unit for freezing water into ice, an ice storage tank for storing the ice, and an HE for facilitating heat transfer between the ice and the refrigerant used in the GSHP. The system can be designed in two configurations: direct expansion ice storage where the refrigerant directly cools the ice or secondary loop ice storage where a secondary fluid transfers heat between the ice and the refrigerant [134].

Ice storage systems offer several advantages over other TES methods such as a high thermal storage density, low cost, and minimal environmental impact. Furthermore, they can be used in conjunction with GSHPs for both heating and cooling, making them a versatile option for heat, ventilation and air conditioning systems [135]. However, there are some limitations such as the need for a large storage tank and precise control to prevent the ice from melting during periods of high demand.

Studies have been conducted to evaluate the performance and efficiency of ice storage systems integrated with GSHPs. For example, Zhang et al. [136] conducted a study on the operation modes of a GSHP integrated with an ice storage system in a commercial building in Beijing, China. The system design and optimal operating mode were analysed through technical and economic comparisons. The results showed an increase in investment by 107.5 % but a decrease in average annual operating cost by 37.85 % compared to conventional air conditioning systems and a payback period of 4.7 years. However, only load ratios of 100 %, 60 %, and 30 % were considered and the study did not cover all possible operating conditions. In another study, Dong et al. [137] modelled the soil heat transfer of GSHPs and used numerical simulation to examine the impact of integrating an ice storage system. The results suggested that decreasing the number of boreholes and increasing their distance balanced the underground heat and cold in the integrated system. Installing a cooling tower or heat recovery system in areas dominated by cooling can address the issue of underground heat imbalance.

A summary of the literature studies on the ice storage-integrated GSHPs along with the operational and climate conditions is shown in Table. 3.

Ice storage, by improving the efficiency and reducing the energy consumption of GSHP systems, can contribute to decreasing greenhouse gas emissions, making the systems more environmentally friendly. However, integrating ice storage with GSHPs adds a layer of complexity to the system, as additional controls, sensors, and management strategies will be required to optimise the operation of both the GSHP and the ice store. Achieving an optimal design and control of these systems will require precise calculations and control algorithms to ensure the system operates efficiently throughout different seasons and varying load conditions, which may prove challenging.

5.2. PCM storage-assisted GSHP systems

The use of PCM storage in GSHPs has attracted significant attention in recent years. Such a configuration utilises the thermal storage properties of a PCM to store and release thermal energy for heating and cooling applications [138]. These materials can store thermal energy during periods of low demand and release it during periods of high demand, thus reducing the thermal load on the heat pump and increasing its efficiency. During the cooling mode of operation, the GSHP absorbs heat from the building and transfers it to the PCM, causing it to melt. During the heating mode of operation, the GSHP extracts heat from the PCM, causing it to solidify. This process allows the GSHP to shift its energy consumption to off-peak periods, reducing the overall energy consumption and increasing the system's COP [139].

The integration of PCM storage with a GSHP system can be achieved through various means. A typical approach involves incorporating a PCM-based TES tank linked to the GHE of the GSHP. Depending on the demand, the PCM-based TES tank either absorbs or releases thermal energy while the GSHP is in operation. Alternatively, PCM can be integrated into building materials such as wall panels and flooring. During the installation of the BHE, a gap is created between the pipes and ground, and grout or backfill is inserted to fill the gap to transfer heat between the ground and the pipes [140]. PCM can also be utilised as a grout or backfill in BHEs to improve heat transfer.

Integrating GSHPs with PCM storage offers several advantages over traditional GSHPs, including a higher thermal storage capacity, which reduces the size of the HE and the ground loop, a reduction of cost, and an increased system efficiency. Additionally, PCM storage can also increase the system's COP by reducing the number of times the GSHP needs to turn on and off. This can lead to significant energy savings especially in systems that are used for long periods of time [141].

Several references have investigated the integration of PCM with GSHPs for heating and cooling applications. In these studies, the performance of the integrated system was evaluated through experiments, numerical simulations, and through economic analysis. In general, the results presented in the references showed that the utilisation of PCM storage-assisted GSHP is suitable for heating and cooling applications and could result in energy savings and improved performance compared to traditional systems. Relevant aspects of these references are discussed in the next paragraphs.

Table 3
Summary of the literature studies on ice storage-integrated GSHPs.

Authors and reference	Type of building / facility	Country and year	Climate conditions [106]	Type of system	HP modelled	Type of study	Major findings
Zhang et al. [136]	Test platform	Beijing, China, 1997	Dwa (continental, dry winter, hot summer), bordering BSk (dry, semi-arid steppe, cold)	Ice storage-based GSHP	Yes	Experimental	Fuel consumption was reduced by 2-2.5 times compared to conventional system
Dong et al. [137]	Test platform	Shanghai, China, 2010	Cfa (temperate, no dry season, hot summer)	Ice storage-based GSHP	Yes	Numerical	The number of boreholes was decreased, while the distance between them was increased.

Benli et al. [142], Benli and Durmuş [143] investigated a GSHP system integrated with PCM for greenhouse heating in Elazig, Turkey. The results showed that the heating COP of the GSHP units was in the range of 2.3 and 3.8 and the COP for the overall system was in the range of 2–3.5. Another study by Wu et al. [144] presented an integrated heating and cooling system in Harbin, China, using a SAGSHP and PCM for short term storage. The system demonstrated an average heating COP of 3.2 in winter. Wang et al. [145] conducted a numerical and an experimental study on a SAGSHP system integrated with PCM located in Harbin, China and found that a good agreement was exhibited between the numerical and experimental results.

Bottarelli et al. [139] performed a numerical investigation on PCMs in conjunction with shallow GHEs and GSHPs. The presented results indicated that incorporating a PCM with a GHE effectively met the instantaneous heating demand by GSHPs, reducing sudden cooling waves and smoothing peak temperatures by up to 0.7 K compared to the case when PCM is not used. Using storage led to an improved COP in the GSHPs and an improved recovery of underground TES for shallow GHEs, mitigating seasonal variations due to weather change.

In [146], the integration of PCM with a GHE of a GSHP system was investigated. A drainage trench filled with PCM served as a GHE with water flowing among the granules. The numerical modelling results showed that the use of PCM was effective in enhancing the working conditions of the heat pump and stability of the working fluid temperature. The PCM also effectively reduced the thermal wave and prevented working fluid freeze, but the system had a lower efficiency during certain seasons caused by the PCM's low thermal conductivity. Additionally, the impact on the surrounding ground thermal field was lessened with the use of PCM, leading to a more compact trench design for the required energy demand.

McKenna and Finn [147] developed a simulation model using TRNSYS for a GSHP system integrated with a cold PCM TES unit in a commercial building in Marseille, France. The authors presented the process of constructing individual models for various components of the system, such as the PCM tank, pumps, fan coil units, heat pump, air handling unit, and the validation and integration of each component into a system model.

In the study by García-Alonso et al. [148], the feasibility of a GSHP system for a single-family house for a European continental climate was analysed through numerical analysis for two cases: a GSHP with SHTES (water) and a GSHP with LHTES (PCM). The results showed that the adoption of the LHTES system resulted in 37 % energy savings and a reduction of 30 % in the required space for the facility.

In the study presented by Wang et al. [149], PCMs were used as grout in place of traditional materials to increase the heat capacity of soil. The impact of this substitution on the heat transfer of BHEs was analysed through 3-D numerical simulations for three models: soil grout, PCM grout, and enhanced PCM grout. The comparison of the heat transfer characteristics showed that the temperature differences of the outlet and inlet thermal fluid for PCM grout and enhanced PCM grout were 67 % and 82 % compared to when soil was adopted as grout.

Zhu et al. [150] studied the performance of a GSHP integrated with a PCM cooling storage system for an office building in Wuhan, China, through numerical simulation. The results an optimal cooling storage ratio of 40 % when considering the initial investment and operation costs, leading to a 34.2 % reduction in annual cost compared to a HGSHP-cooling tower system.

Qi et al. [151] performed a numerical simulation to study the melting of PCM grout in a GSHP system and found that PCM is a suitable backfill material owing to its stable phase change temperature and small thermal effect radius. The heat transfer rate and efficiency of the GHE improved with higher initial ground temperature and larger pipe spacing. However, the heat transfer rate was noticed to be more sensitive to pipe spacing factor compared to the initial ground temperature.

Li et al. [152] conducted a numerical study of a U-tube HE with backfill materials of shape-stabilised phase change material (SSPCM) and crushed stone concrete. The results showed that the use of SSPCM as backfill material increased the total heat storage capacity by 1.23 times and reduced the influence radius by 90 % compared to crushed stone concrete. These allowed for more boreholes to be considered in the project, resulting in 1.37 times higher heat exchange compared to crushed stone concrete. In another case study, Carvalho et al. [153] demonstrated that a 50 % reduction in electricity costs for winter space heating is possible through the use of a PCM-based GSHP system.

Jones and Finn [154] presented simulation models of a retrofit installation of a building with a GSHP and PCM-based TES. The model was based on forward finite difference method and integrated into the EnergyPlus simulation program using MATLAB and the building controls virtual test bed environment. It simulated a 10-h long TES charging and discharging period in under 15 s and achieved a discharging heat transfer accuracy to within 2.5 % of experimental results.

In the study by Kong et al. [155], micro-encapsulated phase change material (MPCM) slurries were tested as heat transfer fluids in GSHP systems. The MPCM particles consisted of methyl stearate as the PCM, microencapsulated with polyurea. The results showed that MPCM slurries are a viable heat transfer fluid due to their higher heat capacity and reliability as they did not show significant damage after 123,252 pump cycles. In addition, the heat load-to-pumping power ratio was improved by up to 34 % and the COP by up to 4.9 %.

McKenna et al. [156] studied the potential of combining geo cooling and TES in a Mediterranean climate as an energy efficient and environment friendly building cooling solution. The study used spherically-encapsulated PCM as the thermal storage medium and developed a PCM-based TES tank model. It was shown that electricity savings of 24-45 % could be achieved for the building under investigation with the combined solution compared to a reference GSHP system.

A numerical model was presented by Chen et al. in [157] to investigate the efficiency of a GSHP system by employing PCMs as grout material. The results demonstrated that the PCM grouts with the thermal conductivity comparable to an ordinary ground improved system efficacy and stability. However, PCM grouts with the lower thermal conductivity deteriorated the system performance. The efficiency of the GHE improved with the higher thermal conductivity of soil and larger Darcy velocity (velocity of groundwater seepage). Moreover, the study suggested that the high thermal conductive PCM grouts were more compatible in the areas with low groundwater.

Lyne et al. [158] investigated the impact of incorporating a high-conductivity PCM in the BHE of a GSHP. A laboratory model was adopted, which used a cylindrical electrical heater with a varying power, surrounded by either soil, PCM, or high-conductivity PCM as grouting material, which was then enclosed in soil. Results showed that the PCM reduced temperature fluctuations and increased the heat pump COP by 81 %, while the high-conductivity PCM increased the COP by 112 %. In another reference, Oruc et al. [159] performed an exergy and energy analysis of a PCM in a combined system consisting of a radiant wall heating employing solar heating and a GSHP. The study found that the energy and exergy efficiencies of the system increased with the use of PCM, particularly with SP26E, leading to a 25 % increment in energy efficiency and a 42 % increment in exergy efficiency.

Yang et al. [160] investigated the thermal efficiency of a VBGHE with PCM backfill, experimentally and numerically. Results demonstrated that PCM backfills reduced the soil interference radius, delayed the soil temperature variation, and improved the heat transfer rate of the VBGHE compared to soil backfill. It was also shown that the choice of PCM and its ratio, phase transition temperature and latent heat, operation time, and alternate cooling and heating operations have a substantial impact on the thermal efficacy of the VBGHE.

Bonamente and Aquino [161] analysed the energy performance of a PCM in a customised GSHP system with TES. The experimental setup is depicted in Fig. 14. The results demonstrated that the use of PCM reduced the electric energy consumption by 18 % and improved the system COP, resulting in lower mid- and end-point environmental impacts. A system supplied by PV panels was found to be the most sustainable option, with mid-point and end-point impacts 78 % and 64 % lower than the baseline scenario. The use of PCMs also reduced global warming impacts by up to 0.108 $kgCO_2e/kWh_t$ for the grid hypothesis and 0.0312 $kgCO_2e/kWh_t$ for the PV hypothesis.

Mousa et al. [162] studied two lab-scale energy pile models to explore the influence of PCM and variable flow rates. The results of the study showed that the PCM reduced the temperature increase slope in the charging process and temperature decrease slope in the discharging process. In turn improving the heat transfer between the HE, concrete, and soil. The PCM and higher flow rate ameliorated the storage capacity and amount of heat stored and extracted. The storage efficiency was improved from 75 % to 80 % corresponding to a flow rate of 735 mL/min.

In [163], the use of building foundation piles as a GHE and incorporating PCM containers into a concrete shell were probed. The study findings demonstrated that the system configuration improved the energy storage capacity, however, resulted in an inefficient temperature distribution during the charging period. The flow transition from laminar to turbulent in GHE improved the storage capacity up to 10 %. The study also emphasised on considering PCMs with the melting temperature compatible with the peak load times.

In [164], a finite element based full-scale model of energy piles was developed to examine the impact of PCMs on its thermal performance considering annual load of an actual building. The model incorporated an actual heat pump performance curve and investigated the influence of PCM melting range and location on performance. The results indicated a 5.2 % improvement in COP during PCM melting and a deterioration of 1.8 % in solid state. Containment of the PCM cylinders within the concrete shell proved more effective than placing them outside. The optimal location was determined in between the centre of the pile and the U-loop.

The study by Alkhwildi et al. [165] proposed a novel GSHP system integrated with a salt hydrate PCM storage tank for buildings in cold climates to damp peak heating loads and remove annual ground thermal loads imbalances. The schematic of the system is depicted in Fig. 15. The simulation findings indicated a significant potential for GHE size reduction in the integrated system, with a melting temperature of 27 °C yielding the most favourable economic results and a GHE size reduction by over 50 %.

A SAGSHP heating system with a PCM storage tank was examined by Han et al. [166]. It was shown that the system effectively utilises solar energy and soil heat, improving the COP of the GSHP. The PCM-based TES tank increased the solar fraction of the system and improved heat storage capacity of the tank, simultaneously reducing its size and temperature fluctuation. The heating performance of the system varied during different heating stages, with higher COP and indoor temperature in the initial and latter heating periods and lower COP and indoor temperature in the middle heating period.

Sunak et al. [167] proposed a novel foundation-based geothermal HE, integrating PCM to reduce construction and installation costs. Thermal performance of the system was assessed through numerical model and the results were validated by running experiments on prototype system. The results exhibited that the use of PCM led to improved thermal performance, energy savings, and reduced greenhouse gas emissions. Additionally, sensitivity studies demonstrated that the thermal performance improved with increasing PCM thermal conductivity and increasing the amount of seasonal heat injection relative to the

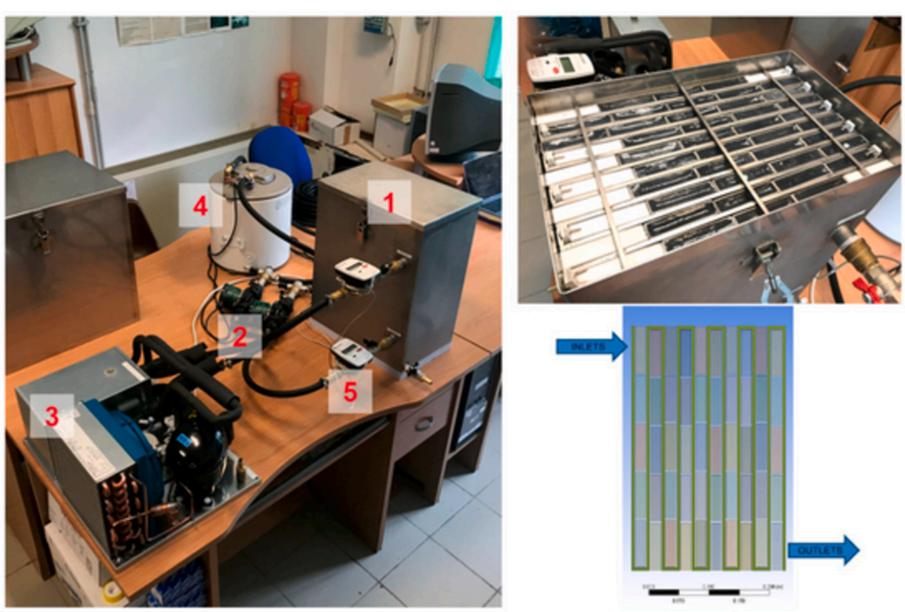

Fig. 14. Experimental layout used in [161]: 1) PCM tank, 2) pumps, 3) chiller, 4) heater, 5) temperature and flow meters.

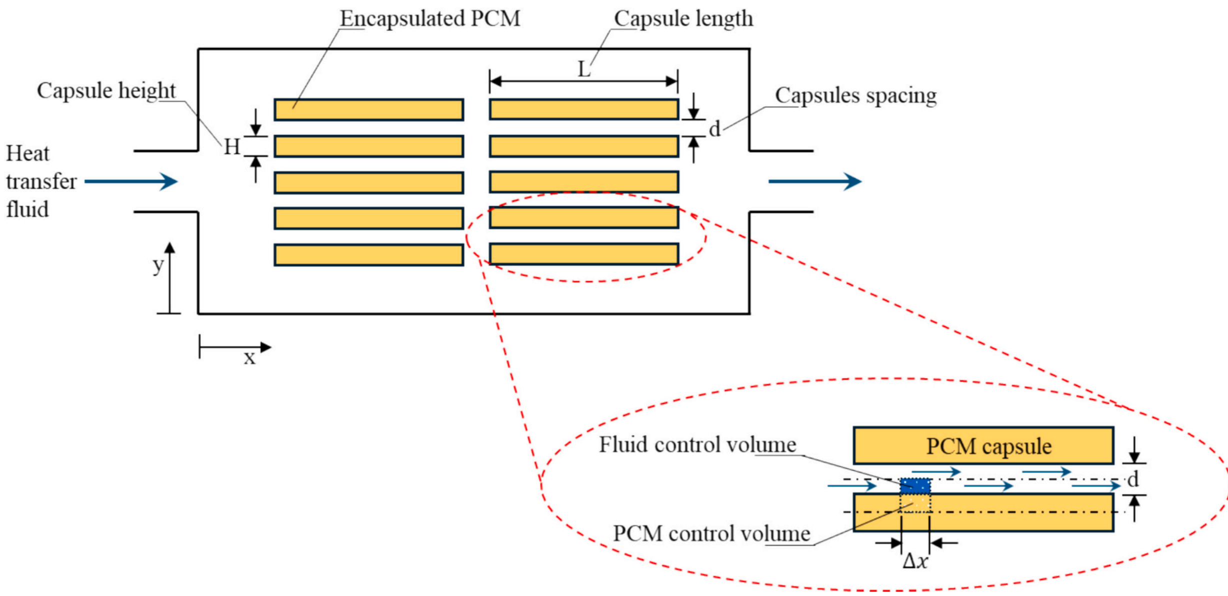

Fig. 15. TES tank with encapsulated PCM (adapted from [165]).

amount of heat extraction.

Pássaro et al. [168] examined the potential benefits of using macro-encapsulated PCM in geothermal boreholes as an enhancer for the performance of a GSHP. The numerical analysis explored the effect of various PCM thermal parameters on heat pump performance, including different operation modes, solidus/liquidus temperatures, and phase transition enthalpies. The results indicated that while the performance of the GSHP was not significantly improved, the macro-encapsulated PCM stabilised the soil and heat pump operation, thus reducing energy expenditure by the system.

Daneshazarian et al. [169] developed a numerical model and analysed the thermal performance of a database of ninety nano-PCM based on different combinations of nine nanoparticle types and ten PCM types. A hierarchy method was adopted to select best nano-PCM based on thermal performance, which was later considered for modelling of TES-integrated GSHP system. The results suggested that incorporating nano-PCM improved the thermal storage efficiency by 24.6 %. The proposed energy system also increased the system COP by 9.5 % compared to a case without PCM integration. Daneshazarian and Berardi [170] integrated nano-enhanced PCM-based TES with a SAGSHP to meet the space conditioning and hot water requirements of a 33-storey residential building. Adding nanoparticles to the PCM increased energy storage capacity by 26.4 %. The COP of the applied TES-integrated GSHP system increased by 27.1 %, resulting in a 36.7 % reduction of building energy consumption.

In [171], three SSPCMs, namely, hexadecane, heptadecane, and octadecane, were tested as backfill to investigate the effect of initial ground temperature and pipe spacing on the BHE performance. The considered SSPCMs compared to commercial PCM grout showed a maximum thermal improvement of 21.4 % in the heating season and of 20.5 % in cooling season. The COP of the GSHP was increased by utilising PCMs as backfill as they minimised the temperature perturbation.

A summary of the literature studies on the PCM storage integrated GSHPs along with the operational and climate conditions is shown in Table 4.

As demonstrated by the references available in the literature, numerical and experimental techniques are typically used to investigate PCM storage-assisted GSHP systems. PCMs are interfaced with GSHP systems mainly in two ways: as PCM-based storage tanks or as a backfill material in boreholes. Current research focuses on enhancing the performance of PCM storage-assisted GSHP systems by evaluating various PCMs to identify optimal thermal properties and phase change temperatures. Researchers are also investigating these integrated systems to maximise load balancing and minimise soil thermal interference radius. Future research may aim to address existing challenges to advance the technology and make PCM storage-assisted GSHPs a viable option for sustainable energy solutions. This will need though development of smart and adaptive control systems to optimise the operation and efficiency of integrated systems. Long-term performance and durability analysis of PCMs and integrated systems will be essential to ensure sustainability and reliability of technology.

6. Sensible-latent heat-based TES-GSHP systems

This section considers systems which integrate both LHTES units and SHTES units with a GSHP. By leveraging both sensible and latent heat storage, these systems can improve overall energy storage efficiency. Latent heat storage, with its higher energy density, can reduce the spatial footprint required for the thermal store. Integrating sensible-latent heat-based TES with a GSHP can smooth out the load profile, reduce peak demand, and improve system reliability. The TES-GSHP systems include PCM integrated with water and soil-based storage systems. A short discussion on each reference found in the literature is provided in the next subsections.

6.1. *PCM-soil based TES-GSHP systems*

The study by Dehdezi et al. [173] found that incorporating MPCM into the soil resulted in a lower thermal conductivity and an increased volumetric heat capacity. The numerical simulations showed that the temperature variation in the ground could be reduced by 3 °C with PCM-modified soil, leading to an improvement in the COP of the heat pump system by over 17 %. The scanning electron microscopy of paraffin wax is shown in Fig. 16.

Bottarelli et al. [174] evaluated the enhancement of shallow GHEs through the incorporation of PCM into the backfill material (soil, water). A 2-D model was used to simulate the heat transfer of a flat-panel GHE. The yearly performance was modelled using numerical simulation, showing that the use of PCM improved the ground thermal wave, increased the COP of the heat pump, and avoided winter thermal exhaustion. The study suggested that the proposed design could lead to shallow horizontal GHEs to improve underground TES systems.

Table 4
Summary of the literature studies on PCM storage-integrated GSHPs.

Authors and reference	Type of building / facility	Country and year	Climate conditions [106]	Type of system	PCM type	HP modelled	Type of study	Major findings
Benli [142], Benli and Durmuş [143]	Greenhouse	Elazig, Turkey, 2005–2006	Csa (temperate, dry summer, hot summer), bordering Dsa (continental, dry summer, hot summer)	PCM storage (tank)-based GSHP	Calcium chloride hexahydrate	Yes	Experimental and numerical	Heat pump COP = 2.3–3.8, System COP = 2.0–3.5
Wu and Zheng [144]	Test facility	Harbin, China, 2005	Dwa (continental, dry winter, hot summer)	PCM storage (tank)-based GSHP	Not otherwise specified (NOS)	Yes	Experimental	Average system COP = 3.2 (winter)
Wang et al. [145]	Test facility	Harbin, China, 2010	Dwa (continental, dry winter, hot summer)	PCM storage (tank)-based GSHP	Calcium chloride hexahydrate	No	Experimental and numerical	Average system COP = 6.49 (winter)
Bottarelli et al. [139]	None	No specified location, 2013	Not applicable	PCM storage (backfill)-based GSHP	NOS	No	Numerical	Incorporating PCMs with GHEs smooth-up the peak temperatures by up to 0.7 K.
Bottarelli et al. [146]	Residential building	Ferrara, Italy, 2015	Cfa (temperate, no dry season, hot summer)	Encapsulated PCM storage (trench backfill)-based GSHP	Paraffin	No	Numerical	PCMs in a drainage trench GHE lead to reduced impact on the thermal field of the ground, but with lower efficiency in spring and autumn.
McKenna and Finn [147]	Commercial building	Marseille, France, 2013	Csa (temperate, dry summer, hot summer)	PCM storage (tank)-based GSHP	NOS	Yes	Numerical	Developed TRNSYS models of an encapsulated PCM-TES tank.
García-Alonso et al. [148]	Test facility	Burgos, Spain, 2013	Cfb (temperate, no dry season, warm summer)	PCM storage (tank)-based GSHP	NOS	Yes	Numerical	A 37 % savings in energy consumption.
Wang et al. [149]	Office building	Shanghai, China, 2014	Cfa (temperate, no dry season, hot summer)	PCM storage (grout)-based GSHP	Mixture of n-decanoic acid and lauric acid (DLC)	No	Numerical	Utilising PCM and enhanced PCM, resulted in temperature gradients (between inlet and outlet thermal fluid) of 67 % and 82 % compared to soil as grout.
Zhu et al. [150]	Office building	Wuhan, China, 2015	Cfa (temperate, no dry season, hot summer)	PCM (tank)-based GSHP	Hydrate sodium sulfate	Yes	Numerical	Maximum cooling storage ratio of 40 %, Annual cost reduction of 34.2 % compared to a common GSHP with cooling tower system.
Qi et al. [151]	Office building	Not specified, 2016	Not applicable	PCM storage (backfill material for vertical U-tube GHE) based GSHP	Paraffin RT27, acid and enhanced acid	No	Numerical	PCM is a suitable backfill material for GSHP systems with improved heat transfer rate and smaller thermal effects radius.
Li et al. [152]	Test facility	Dalian, China, 2016	Dwa (continental, dry winter, hot summer)	PCM storage (backfill of U-tube HE)-based GSHP	Mixture of decanoic acid and lauric acid	No	Experimental and numerical	PCM as backfill material increased the total heat storage capacity and heat exchange by 1.23 times and 1.37 times, respectively, while reducing the influence radius by 90 %.
Carvalho et al. [153]	Public building	Coimbra, Portugal, 2012	Csa (temperate, dry summer, hot summer), bordering Csb (temperate, dry	PCM storage-based GSHP	S46 salt hydrate	Yes	Numerical	Adding PCM reduced 50 % energy consumption.

(continued on next page)

Table 4 (*continued*)

Authors and reference	Type of building / facility	Country and year	Climate conditions [106]	Type of system	PCM type	HP modelled	Type of study	Major findings
Jones and Finn [172]	Municipal building	Coimbra, Portugal, 2013	summer, warm summer) Csa (temperate, dry summer, hot summer), bordering Csb (temperate, dry summer, warm summer	PCM storage-based GSHP	S46 salt hydrate	Yes	Numerical	EnergyPlus could be used as tool to optimise PCM and GSHP system.
Kong et al. [155]	Laboratory experiments and field-testing	Fort Hood, Texas, United States, 2017	Cfa (temperate, no dry season, hot summer)	Microencapsulated PCM storage (slurry)-based GSHP	Methyl stearate microencapsulated with polyurea	Yes	Experimental	Utilising MPCM slurries enhanced heat load-to-pumping power ratio by up to 34 % and COP of the GSHP system by up to 4.9 %.
McKenna et al. [156]	Office building	Marseille, France, 2017	Csa (temperate, dry summer, hot summer)	Spherically-encapsulated PCM storage based GSHP	NOS	Yes	Numerical	Geo-cooling combined with spherically-encapsulated PCMs based TES showed potential for electricity savings of 24-45 %.
Chen et al. [157]	Office building	Nanjing, China, 2017	Cfa (temperate, no dry season, hot summer)	PCM storage (grout for a vertical U-tube HE) based GSHP	Paraffin SSPCM	Yes	Numerical	Utilising PCM grouts that possess thermal conductivity similar to conventional grouts, enhanced both the system efficiency and stability.
Lyne et al. [158]	Laboratory model	Not specified, 2019	Not applicable	PCM storage (grout in BHE) based GSHP	Graphite-PCM "PureTemp2"	Yes	Experimental	Maximum system COP increased by 81 % with PCM and 112 % with graphite-enhanced PCM.
Oruc et al. [159]	Residential building	Not specified, 2019	Not applicable	PCM storage (embedded radiant wall heating for buildings) based GSHP	C13-C24, C18, SP21EK 23, SP26E	Yes	Analytical	Energy efficiency increased from 62 % to 87 % and the exergy efficiency increased from 14 % to 56 % when the SP26E PCM was used.
Yang et al. [160]	Lab-scaled test facility	Jiangsu, China, 2019	Cfa (temperate, no dry season, hot summer)	PCM storage (backfill) based (borehole) GSHP	Mixed acid composed of decyl acid and lauric acid, oleic acid	No	Experimental and numerical	The soil thermal interference radius of a VBGHE with PCM backfill was reduced compared to traditional soil backfill in both summer and winter modes, with reductions ranging from 86.5 % to 87.8 %.
Bonamente and Aquino [161]	Laboratory test facility	Perugia, Italy, 2020	Cfa (temperate, no dry season, hot summer)	PCM storage (tank)-based GSHP	RT-6 & RT-27	Yes	Experimental and numerical	PCMs reduced electric energy consumption by 18 % and improved system COP, resulting in lower mid- and end-point environmental impacts.
Mousa et al. [162]	Lab-scaled experiment test rig	Ontario, Canada, 2020	Dfb (continental, no dry season, warm summer)	PCM storage-based (containers in energy piles) GSHP	Paraffin wax	No	Experimental and numerical	PCM usage improved heat storage and extraction efficiency in the energy pile models, with the storage efficiency increasing up to 98 % for 2100 mL/min flow rate.

(*continued on next page*)

Table 4 (*continued*)

Authors and reference	Type of building / facility	Country and year	Climate conditions [106]	Type of system	PCM type	HP modelled	Type of study	Major findings
Mousa et al. [163]	lab-scaled test facility	Ontario, Canada, 2021	Dfb (continental, no dry season, warm summer)	PCM storage-based (foundation piles) GSHP	Paraffin wax	No	Experimental and numerical	Increasing the flow rate from laminar to turbulent regions inside GHE resulted in energy storage capacity increment by 10 %.
Mousa et al. [164]	Actual building load	Toronto, Canada, 2022	Dfb (continental, no dry season, warm summer)	PCM storage-based (energy piles) GSHP	RT5HC	Yes	Numerical	PCMs in energy piles improved the system COP by up to 5.2 % during melting. Multiple PCMs with varying melting temperatures resulted in an enhancement of up to 26 %.
Alkhwildi et al. [165]	Residential building	Columbus, Ohio, United States, 2013–2014	Cfa (temperate, no dry season, hot summer), bordering Dfa (continental, no dry season, hot summer)	PCM storage-based GSHP	Salt hydrate (S8, S17 and S27)	Yes	Numerical	A 50 % reduction in GHE was achieved by utilising PCM based TES-GSHPs
Han et al. [166]	Building	Harbin, China, 2008	Dwa (continental, dry winter, hot summer)	PCM storage-based SAGSHP	Salt hydrate based PCM ($CaCl_2$ $6H_2O$)	Yes	Numerical	In the heating period, the average COP of the SAGSHP system with a PCM storage was found to be 3.28, with higher COP in the initial and latter heating periods (highest value: 5.95).
Shukla et al. [167]	Ecofarm	Southern Ontario, Canada, 2020	Dfb (continental, no dry season, warm summer)	PCM storage-based (filled in foundation caisson) GSHP	Paraffin wax	Yes	Numerical	The use of PCM leads to improved thermal performance and energy savings in a system, as demonstrated by sensitivity studies, with increased thermal conductivity and reduced greenhouse gas emissions.
Pássaro et al. [168]	NOS	Not specified, 2022	Not applicable	PCM storage-based (U-type borehole) GSHP	Paraffin wax	Yes	Numerical	The application of macro-encapsulation provided a stabilising effect to the soil and heat pump operation, which helped to reduce the energy expenditure of the system.
Daneshazarian et al. [169]	Residential building	Toronto, Canada, 2022	Dfb (continental, no dry season, warm summer)	PCM storage (backfill) based (borehole) GSHP	A database of 90 nano-PCM	Yes	Numerical	Nano-PCM based TES improved the system COP by 9.5 % compared to a case without PCM.
Daneshazarian and Berardi [170]	Residential building	Toronto, Canada, 2023	Dfb (continental, no dry season, warm summer)	PCM storage (backfill) based (borehole) SAGSHP	Nano-enhanced PCM: SavE OM 8 with graphene nanoparticles	Yes	Numerical	The system COP of the proposed TES-integrated SAGSHP increased from 3.64 to 4.40.
Deng et al. [171]	NOS	Hefei, Anhui, China, 2023	Cfa (temperate, no dry season, hot summer)	PCM storage (backfill) based (borehole) GSHP	SSPCM (Hexadecane, heptadecane, octadecane)	Yes	Numerical	The COP of the GSHP is increased by utilising PCMs as backfill as they minimise the temperature perturbation.

In the study by Bottarelli and Gallero [175], the energy performance of a DSHP combined with a novel flat-panel horizontal ground heat exchanger (HGHE) filled with a mixture of sand and PCM was analysed through numerical simulations. The layout of the proposed system is shown in Fig. 17. The simulations compared different heat pump types (GCHP, air-source heat pump, and DSHP) and configurations under real operating conditions for both space heating and cooling. The findings showed that the combined system is a promising solution for building air conditioning, particularly in high latitude Southern European countries where cooling demand is high, and it offers improved summer thermal performance compared to winter. The use of a high thermal conductivity PCMs as backfill material improves the energy performance of the system. The dual-source functionality of the DSHP and the flat-panel HGHE optimises heat pump performance and reduces HGHE length, resulting in reduced installation costs. It also prevents the use of glycol, which has cost and environmental benefits.

In a study by Aljabr et al. [176], the impact of adding MPCMs to the borehole grout in a GCHP system was analysed numerically. The results showed that incorporating PCM reduced the length of the BHE, but only if a material with the right properties is chosen, i.e., mass, thermal conductivity, and melting temperature. The optimal melting temperature was reported to be an exact average of the fluid entering temperature to the heat pump for peak design condition and the undisturbed ground temperature. Improving grout thermal conductivity was found to be more cost-effective instead of adding a PCM to decrease the BHE length.

Javadi et al. [177] examined the energy storage capacity and thermal conductivity of three novel grouting materials (enhanced grout, enhanced grout with MPCM, and enhanced grout with SSPCM) in combination with 3-D numerical simulation and laboratory scale prototyping. The results showed that the column with enhanced grout had the highest heat flux, while the inclusion of the MPCM resulted in 37 % lower heat flux. The grout column with SSPCM had a smaller mushy zone than the MPCM column, but due to its lower phase change temperature and high thermal conductivity, it was deemed inferior to the MPCM solution. The results suggest that an enhanced grout has high thermal conductivity and adding MPCM to it improves its energy storage capacity, making it a promising solution for BTES systems.

The study by Bottarelli et al. [178] found that adding PCM to the GHE of a GSHP impacted the heat transfer, moderating high temperatures in summer and low temperatures in winter. Due to cost restrictions, the amount of PCM used in the study was limited, but the results suggested prioritising PCM use in extreme weather conditions. The study also showed a good performance of the heat pump. However, the effect of the PCM was restricted, potentially due to constrained loop length, material per trench, and low thermal conductivity of the PCM granules.

Fei et al. [179] proposed a new energy screw pile concept (shown in Fig. 18) which integrated PCM. Numerical simulation of the GSHP unit was performed studying several PCM-solid mixtures, PCM phase transition temperature, moisture conditions, and ground heating plans. The proposed energy screw pile with an adequate PCM-solid mixture, reduced HE fluid temperature. A higher effective thermal conductivity of PCM-solid mixture slowed down phase transition process and lowered the fluid temperature, resulting in improved COPs during cooling mode. The study demonstrated that phase change temperature of the PCM is a key factor in the selection, with high temperatures preferred for constant heat rejection.

Table 5 summarises the literature studies on PCM-soil storage integrated GSHPs.

Most of the studies found in the literature utilised numerical methods to investigate the impact of enhanced grout material by incorporation of different PCMs on the performance of GHEs and the heat pump. Current research findings show that the use of high thermal conductivity PCMs improves the energy performance of the system. Although incorporation of MPCM and SSPCM in the grout material reduces the heat flux, it however increases the energy storage capacity of the material which in turn can reduce ground thermal depletion — a major concern with respect to the widespread adoption of GSHPs as discussed in Section 2.2.

6.2. PCM-water based TES-GSHP systems

Alkhwildi et al. [165] presented a novel GSHP system with an integrated salt hydrate PCM-water storage tank for residential dwellings in cold climates to reduce peak heating loads and remove annual thermal load imbalance of ground. Simulation results showed significant potential for the size reduction of the GHE with a PCM-water storage tank. A 27 °C melting temperature yielded the most profitable results and a GHE size reduction by over 50 %.

Teamah et al. [180] conducted a numerical study of a residential heating system with a GSHP coupled with a TES unit. Water-based and hybrid (water and PCM) storage systems were analysed for a house in Toronto, Canada, on a very cold day as an extreme case. Results showed that a hybrid tank with 50 % PCM reduced the storage volume by 65 % while providing the same heating capability. Operating temperature ranges and the packing ratio influenced the thermal buffering capacity, with lower ranges and higher ratios leading to better performance.

Jahangir and Labbafi [181] conducted a study on the performance improvement of a *Dunaliella salina* microalgae system by integrating a GSHP system with a TES tank using PCM-water. The study investigated

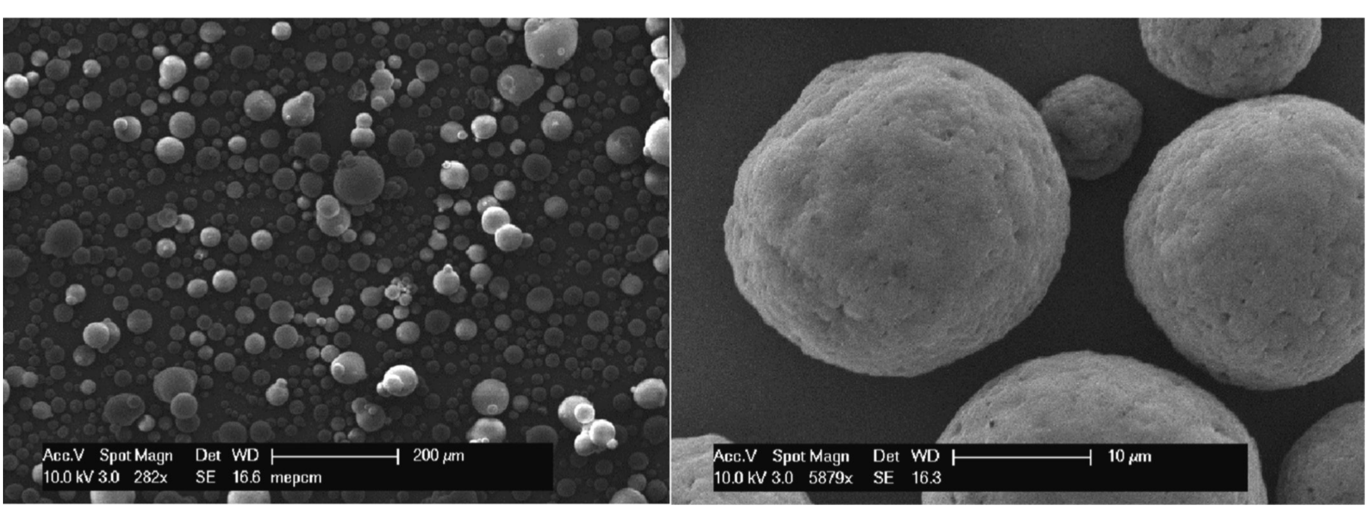

Fig. 16. Scanning electron microscopy micrographs of a MPCM (paraffin wax) [173].

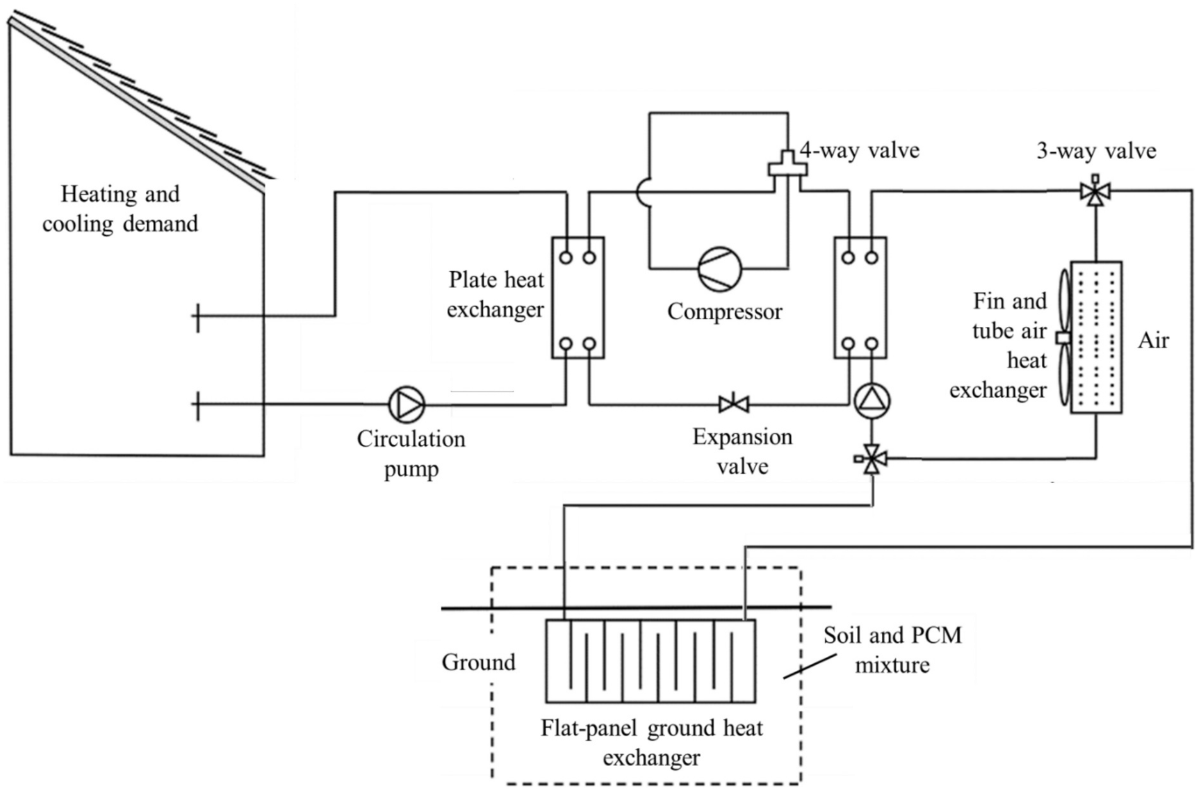

Fig. 17. Layout of the flat-panel HGHE integrated DSHP system (adapted from [175]).

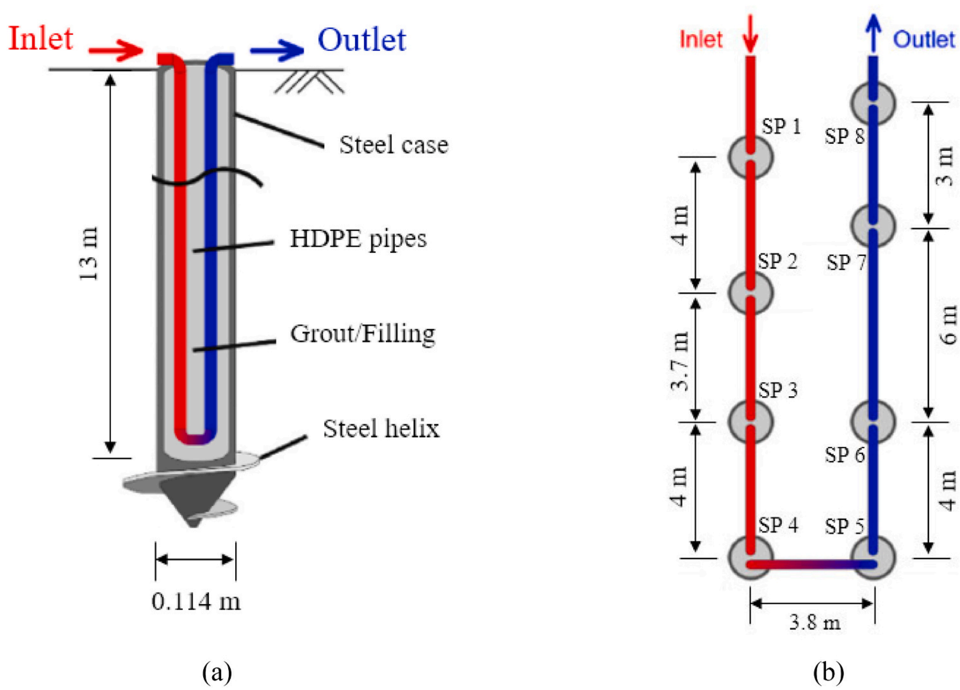

Fig. 18. A typical energy screw pile (adapted from [179]): (a) schematic vertical cross section, and (b) plan view of the screw pile group.

the effect of PCM quantity, fluid circulation flow rate, and nanoparticle usage on the pool water temperature, microalgae growth rate, and system performance. The design and analysis were performed using the Design-Expert software and a central composite solution method. Results showed that system integration improved the COP by 48.7 % in the cooling mode and 53.7 % in the heating mode. The weekly microalgae production was also increased by 54 % in the cooling mode and by 27.6 % in the heating mode.

Zhang et al. [182] conceptualised a novel GHE called underground thermal battery (UTB) which could be installed in shallow and 10 times smaller boreholes compared to conventional VBGHEs. Full scale simulations were performed to investigate the UTB performance and

Table 5
Summary of the literature studies on PCM-soil storage integrated GSHPs.

Authors and reference	Type of building / facility	Country and year	Climate conditions [106]	Type of system	PCM type	HP modelled	Type of study	Major findings
Dehdezi et al. [173]	Test facility	Nottingham, UK, 2011	Cfb (temperate, no dry season, warm summer)	PCM-soil storage (grout)-based GSHP	Paraffin wax (MPCM)	No	Numerical	PCM based system improved the COP of heat pump system by >17 %.
Bottarelli et al. [174]	Residential building	Ferrara, Italy, 2015	Cfa (temperate, no dry season, hot summer)	PCM-soil-water storage (backfill)-based GSHPs	Paraffin	Yes	Numerical	PCMs in backfill material enhanced the performance of shallow GHEs by smoothing thermal waves.
Bottarelli and Gallero [175]	Test facility	Ferrara, Italy, 2015	Cfa (temperate, no dry season, hot summer)	PCM-sand storage (backfill)-based DSHP with a flat-panel HGHE	Paraffin A8, paraffin A24	Yes	Numerical	DSHP systems with a flat-panel GHE and PCM backfill material showed better efficiency and heat flux per trench length.
Aljabr et al. [176]	Residential building	Columbus, Ohio, United States, 2021	Cfa (temperate, no dry season, hot summer), bordering Dfa (continental, no dry season, hot summer)	MPCM-soil (grout) storage based GSHPs	Paraffin	Yes	Numerical	Adding PCM to the borehole grout reduced the BHE length, but optimal results depend on the thermal conductivity of the PCM relative to the grout material.
Javadi et al. [177]	Laboratory-scale prototype	Not specified, 2022	Not applicable	Enhanced grout-microencapsulated PCM, enhanced grout-SSPCM storage based GSHPs	NOS	No	Experimental and numerical	Grout with MPCM had the best heat absorption/ storage performance during phase transition.
Bottarelli et al. [178]	Test facility	Ferrara, Italy, 2020-2021	Cfa (temperate, no dry season, hot summer)	(Granular, macro-encapsulated) PCM-sand (backfill) storage based GSHPs	Paraffin hydrated salts	Yes	Experimental	Winter COP of multi-source heat pump was always larger than 5
Fei et al. [179]	NOS	Melbourne, Australia, 2022	Cfb (temperate, no dry season, warm summer), bordering Cfa (temperate, no dry season, hot summer)	PCM-sand, PCM-concrete, PCM-sand-concrete storage based GSHPs	Paraffin	No	Numerical	A PCM-solid mixture with higher thermal conductivity improved COP by slowing down the PCM phase transition and reducing fluid temperature to the GSHP.

compared to conventional VBGHEs and PCM-enhanced VBGHEs. The results showed that the UTB led to improved GSHP operation due to its large thermal mass and latent heat. The UTB also eliminates the risk of PCM leaking to the surrounding soil as the PCMs are fully immersed in water and protected from moving parts.

Kimiaei et al. [183] conducted a numerical study and investigated different configurations of a GSHP with an electric battery, water-based TES, and PCM-based TES. In the PCM-water storage based GSHP, 75 %

Table 6
A summary of the literature studies on PCM-water storage integrated GSHPs.

Authors and reference	Type of building / facility	Country and year	Climate conditions [106]	Type of system	PCM type	HP modelled	Type of study	Major findings
Alkhwildi et al. [165]	Residential building	Columbus, Ohio, 2013–2014	Cfa (temperate, no dry season, hot summer), bordering Dfa (continental, no dry season, hot summer)	PCM-water storage based GSHPs	Salt hydrate (S8, S17 and S27)	Yes	Numerical	A 50 % reduction in the GHE size was achieved through PCM-water storage-based GSHPs
Teamah and Lightstone [180]	Residential building	Toronto, Canada, 2019	Dfb (continental, no dry season, warm summer)	PCM-water storage based GSHPs	Capric acid, lauric acid, myristic acid, palmitic acid	Yes	Numerical	PCM-water based TES reduced the storage volume by 65 % compared to using only water storage.
Jahangir and Labbafi [181]	Test facility	Bandar Abbas, Iran, 2022	BWh (dry, arid dessert, hot)	PCM-water storage based GSHPs	$CaCl_2$	Yes	Numerical	PCM-water storage-based GSHP improved COP by 48.7 % in a cooling mode and 53.7 % in a heating mode.
Zhang et al. [182]	NOS	Not specified, 2019	Not applicable	PCM-water storage based (UTB), PCM integrated VBGHE TES-GSHPs	Salt hydrates	No	Numerical	UTB outperforms a conventional VBGHE by better regulating the water temperature for a GSHP
Kimiaei et al. [183]	Residential building	Quebec, Canada, 2023	Dfb (continental, no dry season, warm summer)	PCM-water storage based GSHPs	S20	Yes	Numerical	A 21.8 % reduction in the GHE size was achieved through PCM-water storage-based GSHPs.

of the tank volume was filled with PCM and 25 % with water, which led to 39 m reduction in borehole length. The results suggested that the PCM-water storage based GSHP system reduced the peak power demand by 65.4 % and total energy demand by 21.8 % compared to conventional system based on electric resistance heaters and an air-conditioning system.

Table 6 summarises the literature studies on the PCM-water storage integrated GSHPs for variable operational conditions and PCM combinations.

The research studies showed that PCM-water based TES-GSHPs offer an advantage of system compactness by reducing the storage volume. The reduction of the storage volume depends on the volume fraction of PCM and water as higher PCM packing ratios offer higher thermal storage capability. This provides a unique opportunity in the near future to investigate novel and innovative BHE configurations instead of conventional VBGHEs.

7. Barriers, limitations, and future perspectives

Despite the significant potential of TES-integrated GSHP systems to enhance energy efficiency and reduce carbon emissions, several issues and challenges must be addressed to fully realise their benefits. All TES-assisted GSHP systems face some common challenges. Even when these systems may provide significant energy savings, notable challenges include high initial costs, complex installation processes, and the need for extensive ground space for heat exchangers. Since an effective heat exchange in GSHP systems relies on suitable ground conditions (e.g. soil type, depth, and thermal conductivity), proper design, sizing, and installation are critical for an optimal performance. Additionally, there are concerns regarding the long-term performance and environmental impact of the systems. Together with this, a lack of awareness among consumers and professionals can hinder widespread adoption.

This section provides a discussion on the barriers, limitations, and future perspectives of the presented systems, aiming to offer a comprehensive understanding of the current state and future potential of TES-GSHP technologies.

7.1. Soil/rock-based TES-GSHP systems

Soil/rock-based TES integrated GSHP systems present both challenges and exciting prospects. On the one hand, the effectiveness of soil/rock-based TES systems is limited by geological constraints. Soil or rock properties (such as thermal conductivity, porosity, and moisture content) impact heat exchange efficiency. Additionally, the installation complexity of the TES systems is another barrier preventing a widespread utilisation of the technology as drilling boreholes or trenches for heat exchange loops can be costly and requires skilled professionals.

Retrofitting soil/rock-based TES systems into existing buildings or infrastructure poses relevant technical and design challenges [184,185]. Space availability is often limited, so the integration of the TES system requires innovative solutions to prevent disrupting existing structures. The system must be designed to fit within the available space while still providing adequate storage capacity and efficient heat transfer.

Ground imbalance is another challenge posed by this type of system. Over time, the stored heat may lead to temperature imbalances in the ground and will thus affect system performance. To prevent this, the system may need periodic maintenance to ensure an optimal heat transfer.

Existing research shows that innovations in drilling techniques can reduce installation costs and improve efficiency, so future perspectives could build on this. Additionally, combining soil/rock-based TES with other renewable sources (e.g. solar or wind) may be useful to enhance overall system performance. Integration with smart controls and predictive algorithms could be explored to optimise system operation.

7.2. Water-based TES-GSHP systems

There are several technical challenges and limitations associated with water-based TES-GSHP systems including geological suitability, water temperature fluctuations, water quality, and installation complexities. Since water-based GSHP systems require access to an aquifer or a water body (such as a lake or river), availability and quality of water sources are relevant limiting factors.

The temperature of water bodies can vary seasonally and this may affect system efficiency. For instance, cold water in winter or warm water in summer may impact performance. In addition, water quality (e.g. salinity, mineral content) affects heat exchanger performance and system longevity. Moreover, an adequate design and installation of water-based GSHP systems involve considerations like water flow rates, permits, and environmental impact assessments.

TTES systems use a thermally insulated, reinforced concrete/steel, storage tank buried underground to limit heat loss [186], whereas PTES systems operate by sealing water and/or gravel pits in the shallow subsurface with a clay and rubber membrane plus floating lid [187]. TTES and PTES are thus less influenced by geological conditions than ATES/BTES. They also provide greater charging but require higher construction costs. PTES tends to decline in performance as depth decreases and, therefore, TTES becomes more efficient [110,188]. PTES is however more reliable compared to other storage methods [189]. TTES and PTES usually store higher temperature fluid (up to 100 °C) and are, as a result, commonly used for district heat networks [190,191]. The large space requirement of PTES, and sometimes TTES, may make them potentially unfeasible for large scale UTES in densely populated areas.

Future prospects may involve combining water-based TES with other renewable sources (e.g. solar-assisted GSHPs) to enhance overall system efficiency. Incorporation of advanced control algorithms could also optimise water flow rates and system operation. Moreover, continued research is required to improve water-based GSHP technology and address its limitations. In summary, while water-based TES-GSHP systems have potential, addressing challenges and embracing innovation will drive their successful adoption [76].

7.3. Ice storage-assisted GSHP systems

Ice storage-assisted GSHP systems have some limitations and may face several barriers preventing their widespread adoption. Designing and integrating ice storage with GSHPs requires careful planning which in turn demands proper sizing, control strategies, and equipment coordination. For instance, the efficiency of the chiller used for ice production impacts overall system performance. Suboptimal chiller operation can reduce energy savings of the integrated energy system. Additionally, ice storage tanks or containers need space within the building or nearby and these space constraints may limit system feasibility. Regular maintenance of ice storage equipment is also necessary to prevent issues such as scaling and corrosion. Overall, installing ice storage systems can be expensive, affecting the overall economic viability of a potential project.

Future development of ice storage-assisted GSHP systems may be promising as these systems could enhance grid stability by shifting cooling loads to off-peak hours. Coupling ice storage with renewable energy sources (e.g. solar) could maximise system benefits. In addition, smart algorithms and predictive controls could optimise ice production and usage [133]. In summary, while ice storage-assisted GSHPs offer relevant benefits, addressing the previous challenges and embracing innovation will help shaping their future [192].

7.4. PCM storage-assisted GSHP systems

PCM storage-assisted GSHP systems have gained significant attention recently, but the technology still faces several challenges. Many PCMs have relatively low thermal conductivity (<10 W/mK), which can limit the power density and overall storage efficiency of an integrated system [193]. The selection of the right PCM is therefore a major challenge. Factors like phase transition temperature, stability, and compatibility with the GSHP system may impact the overall system performance.

Another challenge is the proper containment and encapsulation of PCMs which is essential to prevent leakage and ensure long-term reliability. Notably, some PCMs may pose health risks due to toxicity or flammability; hence, assessing environmental impact and lifecycle aspects is vital for large-scale implementation.

Future prospects for PCM storage-assisted GSHP systems may involve integration with smart grids and energy management systems to allow TES systems to actively participate in demand response programs and provide ancillary services to the electricity grid. Through bidirectional communication and coordination with the grid operator, the TES system may respond to signals and adjust its operation to support grid stability and reliability [194,195].

Real-time data on energy consumption, storage levels and system performance could be collected and analysed to gain insights into system behaviour and optimise operation of PCM storage assisted GSHP systems. This data-driven approach would enable proactive maintenance, identification of potential issues and predictive modelling for system performance optimisation [196–198].

Recent advancements in encapsulation show that innovations in PCM containment technology could enhance safety and efficiency. In addition, integration of PCMs with other energy storage methods (e.g. SHTES) could optimise the overall system thermal performance. In order to improve system operation, intelligent control strategies could be also implemented. In summary, addressing the limitations discussed and embracing innovation will shape the future of PCM storage-assisted GSHP systems [199,200].

7.5. PCM-soil based TES-GSHP systems

PCM-soil based TES-GSHP systems combine the benefits of sensible and latent TES methods. The literature studies on these systems have reported that utilisation of PCM-modified soil could reduce the variation in ground temperature and can lead to shallow GHEs [173], [174]. However, the thermal conductivity of PCM-modified soil is crucial in determining the performance of PCM-soil based systems, as a relatively low thermal conductivity may affect heat transfer efficiency in the soil.

For these type of systems, another barrier is the PCM-soil interaction. This is because soil properties are dependent on several parameters (e.g. moisture content, granularity, porosity) which may impact PCM behaviour. Thus, ensuring the mutual compatibility of PCM and soil is essential. Similarly, incorporating PCM has its advantages but only if a material with the right properties is chosen (i.e. mass, thermal conductivity, and melting temperature) [176].

Other technical challenges associated with the PCM-soil based technology include depth considerations as an inadequate placement of the PCM-soil layers will affect system performance and the long-term stability and durability of the PCM. Moreover, installation requires expertise and precision, making it onerous.

To overcome the aforementioned challenges, future research could focus on developing high-conductivity PCMs for better system performance. For instance, improving grout thermal conductivity was found to be more cost-effective than adding a PCM to decrease the BHE length [176]. In this regard, evaluating the energy storage capacity and thermal conductivity of novel grouting materials such as enhanced grout, enhanced grout with MPCM, and enhanced grout with SSPCM is another promising prospect [177]. Additionally, development of innovative design concepts of GHEs and smart controls based on advanced control algorithms to benefit from several PCM-soil mixtures, PCM phase transition temperature, moisture conditions and ground heating plans could optimise system operation further.

7.6. PCM-water based TES-GSHP systems

PCM-water based TES integrated GSHPs offer a significant potential for size reduction of the GHE with a PCM-water storage tank [165] while providing the same heating capability. As several combinations of GHE size and PCM storage tank size can achieve annually-balanced GHE thermal loads, finding the optimal combination of GHE and PCM tank size is an important challenge. Factors to consider include drilling and GHE installation cost, PCM tank installation cost, and physical space constraints and their associated cost.

Many PCMs have relatively low thermal conductivity, which affects heat transfer efficiency in water. Therefore, choosing the right PCM is a challenge because factors like phase transition temperature, stability, and compatibility with the GSHP system impact performance. Also, operating temperature ranges and the packing ratio can influence the thermal buffering capacity, with lower ranges and higher ratios leading to better performance [180]. Selection of an optimal packing ratio based on thermal capacity considering space constraints is another challenge for PCM-water based systems. There are also some challenges associated with PCM containment as proper containment and encapsulation of PCMs are essential to prevent leakage and ensure long-term reliability.

To overcome the previous challenges, key design variables for the optimal combination of GHE-storage tank size and packing ratio should be investigated further to facilitate the design process. With regards to potential future work, integrating PCM-water storage with other SHTES methods could optimise overall system performance. Also, the design and implementation of intelligent control strategies may be conducive to improve system operation, whereas innovations in PCM containment technology would enhance safety and efficiency. In summary, while PCM-water storage-assisted GSHP systems have a bright potential, addressing the highlighted challenges and embracing innovation will shape their future.

8. Conclusions

Several countries around the world are determined to reduce carbon emissions to limit the effects of climate change. Given that the energy sector is a major contributor to greenhouse gas emissions, the global landscape faces the unique challenge of transitioning to environmentally friendly technology while keeping up with the growing energy demand. In this regard, GSHP systems are promising and their adoption is expected to grow worldwide as countries progress in decarbonising heating and cooling system.

The integration of TES technology with GSHPs is a promising approach to maintain the ground energy balance and improve the energy efficiency of heating and cooling systems. Although these attributes have been identified by several references, a comprehensive and systematic review of the advancements and developments in the field of TES-assisted GSHPs was yet to be conducted. This paper thus constitutes a unique and unifying exercise providing a detailed analysis of the different experimental, numerical, and theoretical studies available in the literature with respect to system performance, climate conditions, and TES techniques. To aid the prospective readers, the examined references have been carefully classified and organised depending on key characteristics of the content and studies presented in each work. Comprehensive tables have been also provided towards the end of each section to summarise relevant aspects of each reference.

The following main conclusions have emerged from this study:

- SHTES integrated GSHP systems offer enhanced thermal performance and energy storage capacity. Among water-based TES systems TTES are the most widely used systems globally. While the UTES technology holds significant potential, its widespread adoption, particularly for ATES systems, is hindered by limited subsurface geological knowledge.

- LHTES assisted GSHP systems are gaining a lot of attention as utilising PCM as a backfill in boreholes improves heat transfer and heat storage capacity. Moreover, it significantly reduces the thermal radius of the borehole (also known as thermal effects radius and soil thermal interference radius).
- A SAGSHP system can significantly reduce the thermal imbalance by increasing ground thermal injection and reducing thermal extraction. Achieving an optimal integration between geothermal energy and other energy sources is crucial for mitigating soil thermal imbalance and enhancing overall system performance. By carefully balancing energy inputs, the system can maintain stable ground temperatures, prevent long-term degradation of thermal efficiency, and ensure consistent operation. This synergy not only helps in maintaining the thermal integrity of the soil but also maximises the energy output, leading to improved efficiency and sustainability of the geothermal system over time.
- One major challenge in LHTES configurations is the low thermal conductivity of PCMs, which in turn leads to slow charging and discharging rates of the thermal store. Other issues encountered by PCMs include phase separation, supercooling/subcooling effects, low latent heat of fusion, low specific heat capacity, poor thermal stability, and high corrosivity. Solutions include adding thermally conductive micro/nanoparticles, finned tubes or conductive meshes, heat pipe heat exchangers, and PCM encapsulation.
- Recent studies on TES-GSHP systems utilising PCM-soil and PCM-water approaches have employed PCM nano-compositing and encapsulation to enhance thermal performance and improve efficiency. Integrating MPCM and SSPCM into grout materials reduces heat flux while significantly increasing the energy storage capacity, which would help mitigate ground thermal depletion—a key barrier to the broader adoption of GSHPs.
- Ensuring long-term thermal performance with minimal environmental impact and a reasonable payback period for GSHPs requires robust control and optimisation strategies. Approaches such as fuzzy logic control can optimise energy consumption in hybrid systems like SAGSHPs due to their ability to process multiple inputs simultaneously—thus offering a suitable alternative for managing the uncertainties and nonlinear behaviour inherent to these systems. Given the complexity of GSHPs, implementing an adaptive control and optimisation system could further enhance their overall efficiency and effectiveness.

In general, future research could explore novel designs like elliptical and oval-shaped U-tubes, and eccentric pipe arrangements for improving closed-loop systems, both with and without solar thermal recharging. Insulating the inner pipes of coaxial GHEs to reduce thermal short-circuiting and lowering thermal resistance in VBGHE designs could significantly enhance performance.

Long-term studies on VBGHE designs are needed to better assess thermal, economic, and environmental impacts, beyond the short-term analyses currently prevalent. Energy pile design software should incorporate mechanical considerations to ensure structural stability under both thermal and load-bearing conditions, particularly where ground freezing is a risk.

LHTES-based units are in general recommended due to their high energy efficiency and high energy density—limiting the amount of space required due to their compact size. It is crucial though to carefully consider the system's operational conditions when selecting the appropriate PCM. Currently there is no comprehensive look-up diagram available to guide this selection process. Furthermore, the development of a unified international standard for testing and analysing PCMs is essential to ensure consistency and reliability across different applications.

In cold climates, advanced control strategies are essential for balancing soil temperatures and optimising GSHP performance in solar-assisted systems. Enhancing the thermal properties of PCM materials and developing cost-effective drilling technology are key to reducing the high upfront costs of GSHP installations.

Finally, future work should also evaluate the role of government policies and regulations in promoting wider adoption of GSHP technology. Clear energy policy on the installation of heat pump systems should be rolled out. This should not only consider the heat pump technology as a low-carbon alternative to meet heating demand but must also emphasise the possibility of deploying reversible heat pump systems to meet cooling requirements in a warming world.

CRediT authorship contribution statement

Arslan Saleem: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Data curation, Conceptualization. **Tehmina Ambreen:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation. **Carlos E. Ugalde-Loo:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Funding acquisition.

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.

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Data availability

No data was used for the research described in the article.

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