





Thermal energy storage–coupled heat pump systems: Review of configurations and modelling approaches

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ABSTRACT

Heat pump systems (HP) are effective technologies for reducing energy consumption and carbon emissions for space heating and cooling of buildings. However, with large-scale deployment, increased electrical demands can place significant stress on power networks. Integrating Thermal Energy Storage (TES) with HP systems offers a viable strategy to mitigate peak power demands and enhance overall energy efficiency by decoupling heat generation and use, hence power intensive heat-generation can be shifted to off-peak and more efficient times. Due to these benefits, the combination of HP and TES systems have gained increasing attention. A number of reviews have examined specific HP-TES configurations and applications, however a comprehensive analysis of HP-TES coupled systems and particularly their modelling approaches remains limited. This paper classifies HP and TES technologies, highlighting their respective benefits and limitations. It further examines various HP-TES system configurations and applications, with a particular focus on modelling approaches. By providing a structured and comparative overview of available modelling methods, this review supports researchers and engineers in selecting the most suitable modelling approach based on system complexity, computational constraints, and specific objectives, facilitating the optimization of HP-TES systems for enhanced energy efficiency and sustainability.

Nomenclature

Abbreviations

| | |
|----------|---|
| ASHP | Air-source heat pump |
| COP | Coefficient of performance |
| DHW | Domestic hot water |
| DX-SAHP | Direct expansion solar-assisted heat pump |
| FDM | Finite difference method |
| FEM | Finite element method |
| FVM | Finite volume method |
| GSHP | Ground-source heat pump |
| HP | Heat Pump |
| IDX-SAHP | Indirect expansion solar-assisted heat pump |
| LHS | Latent heat storage |
| LHTES | Latent heat thermal energy storage |
| PCM | Phase change material |
| SAHP | Solar-assisted heat pump |
| SHS | Sensible heat storage |
| SHTES | Sensible heat thermal energy storage |
| TCS | Thermochemical storage |
| TES | Thermal Energy Storage |
| WSHP | Water-source heat pump |

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(continued)

Abbreviations

| | |
|-------------------|---|
| Symbols | |
| A | Area (m ²) |
| c_p | Specific heat capacity (kJ/kg·K) |
| T | Temperature (K) |
| U | Overall heat transfer coefficient (W/m ² ·K) |
| k | Thermal conductivity (W/m·K) |
| \dot{Q} | Thermal power (kW) |
| L | Diameter of tank (m) |
| m | Mass (kg) |
| \dot{m} | Mass flow rate (kg/s) |
| t | Time (s) |
| Subscripts | |
| i | Node index |
| loss | Thermal losses |
| massflow | Mass flow |
| edge | Edge of the tank |
| amb | Ambient environment |

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1. Introduction

Heating and cooling account for over 50 % of global energy consumption and 40 % of CO₂ emissions [1]. Space heating, in particular, constitutes the largest energy demand in households located in temperate regions. For example, in the UK, domestic and commercial heating is responsible for around 20 % of annual carbon emissions [2]. Similarly, in New Zealand, space heating represents 34 % of household energy use, which is the largest single component of residential energy demand [3].

Electrifying heating systems present a viable alternative to fossil fuel-dependent systems, particularly as electricity grids become increasingly decarbonized. Heat pumps (HPs) are a proven technology for reducing energy consumption and CO₂ emissions in heating and cooling applications. HPs can be categorized into air source, ground source, and water source types [4]. Using thermodynamic processes to transfer heat, they achieve significantly higher energy performance than traditional fossil fuel combustion systems. The International Energy Agency (IEA) estimates that HPs could satisfy 90 % of global heating needs with a lower carbon footprint than gas-fired condensing boilers [5]. For instance, one study projected carbon emission reductions of 25–90 % from using a ground source heat pump (GSHP), compared to gas and oil boilers in the UK [6]. On a larger scale, the IEA estimates HPs globally have the potential to reduce CO₂ emissions by at least 500 million tonnes in 2030 [7].

Despite these benefits, the widespread adoption of HPs presents challenges for power networks. Widespread uptake of HPs can require significant power-system upgrades to facilitate increased peak power and electricity demands [8]. However, studies suggest that coupling HPs with thermal storage could reduce these costs by as much as 10 % [9]. Demand response provides a cost-effective approach to manage electricity demand by shifting consumption to align with supply conditions, mitigating the impact of increasing intermittent renewable generation. Strategies such as demand curtailment, valley filling, and load shifting can enhance grid flexibility without significant additional costs. Integrating HPs with thermal energy storage (TES) aligns with this approach by decoupling electrical energy consumption from thermal energy delivery [10]. The HP charges the TES during off-peak times. Subsequently, the heating or cooling is dispatched from the TES to meet heat demands. This load-shifting strategy can significantly reduce peak power demands. One study projected peak demand reductions for residential buildings between 25 and 45 % [11]. Furthermore, the economic feasibility of HP-TES systems is enhanced under time-variable electricity pricing. Operators can strategically charge the TES during periods of low electricity prices (e.g., overnight or during off-peak times). Subsequently, discharging the TES during peak demand periods mitigates exposure to high peak-demand charges, resulting in a reduction in overall electricity costs [12]. Demand response with thermal systems is also known as Power-to-Heat (P2H) [13]. Additionally, HP systems can be applied and demand-response utilised in district heating and cooling systems, such as Fourth Generation District Heating (4GDH) [14], and Fifth Generation District Heating and Cooling (5GDHC) [15]. In buildings with PV systems, TES also offers an alternative to battery storage for enhancing flexibility and self-consumption, particularly when integrated with HP-based demand response strategies.

Several reviews have been conducted on TES and HP systems separately. HP systems have been extensively examined, including air-source, ground-source, water-source systems, and hybrid systems [16–19], with a focus on their thermodynamic performance, environmental impact, and economic feasibility. Chua et al. [19] summarised solutions to improve COP and reduce carbon emissions, and present novel applications for specific industries. Ni et al. [20] reviewed recent developments of HP technologies and their application in China, including a comprehensive classification of HP types with their benefits and specific challenges. Recent reviews on TES highlight advances in various storage types, including sensible heat storage (SHS), latent heat

storage (LHS), and thermochemical storage (TCS) [21–24]. Alva et al. [25] examined TES applications and the thermal properties of storage materials, offering insights into operational challenges, design considerations, and cost models. Sadeghi [23] focused on TES development, emphasizing thermo-physical properties, real-world applications, and integration with renewable energy systems. Chavan et al. [21] reviewed TES applications across various sectors, such as waste heat recovery, cooling of heavy electronic equipment and biomedical applications.

To realise the benefits of coupling HP and TES systems, further studies reviewed HP-TES system configurations, material properties, and applications for reducing peak power demand and costs while enhancing performance. Osterman et al. [26] reviewed configurations of air and ground source HPs coupled with phase change materials (PCM) for heating and cooling in buildings. They assessed reductions in investment and operational costs and provided control strategies for power grid operators to reduce peak demand. Ermel et al. [27] reviewed configurations and arrangements for ASHP-TES, noting an average performance increase of 27 % when TES is added. They reviewed various topics including: common system configurations, utilizing TES to support HP operation in cold climates where defrosting is required, general enhancements in HP-TES system performance, sizing ASHP-TES systems for increased performance, and summarised the challenges of integrating TES in ASHP systems. Gu et al. [28] investigated PCM-HP systems, classifying PCM types, analysing their thermal properties, and discussing applications for thermal energy storage and evaporator defrost. Saleem et al. [29] reviewed recent advancements in TES-GSHP systems, with a focus on integrating GSHP with sensible heat thermal energy storage (SHTES) and latent heat thermal energy storage (LHTES). They examined various system types, applications, and benefits while also addressing the limitations of TES-assisted GSHP systems. Reviews of HP-TES systems to date have been limited to specific technological combinations and applications, a comprehensive review of the coupled HP-TES systems has not yet been conducted. Additionally, while many papers simulate HP-TES systems to explore their benefits, the modelling methodologies across technologies are diverse and modelling methods for HP-TES systems have not yet been comprehensively reviewed.

The modelling approaches for evaluating HP-TES systems are widely varied and have significant impact on model accuracy. Badescu [30] examined a mathematical model for integrating SHS and solar HPs for space heating. Renaldi et al. [31] introduced a mixed integer linear programming (MILP)-based model of HP-TES systems for the optimal design of low carbon heating systems. This model considered the adverse effects of undersized HPs and addressed the generally high operating cost problem of systems. They found MILP-based optimization frameworks with low-complexity models can solve problems relatively quickly compared to dedicated software tools such as TRNSYS. In order to reflect transient behaviours and enhance control optimization, further studies, such as Finck et al. [32], presented a dynamic system model for HP-TES systems to adapt the energy consumption of buildings to fluctuations in supply. This model is also suitable for use in online model predictive control. Diller et al. [33] presented a dynamic programming-based method for optimal control of a cascaded HP system with TES, which can achieve significant cost savings and reduced power consumption compared to conventional rule-based control. However, to date, no comprehensive review of modelling methods for HP-TES systems has been conducted.

This paper presents a comprehensive review of HP-TES coupled energy systems for space heating and cooling applications. The various TES and HP technologies, and their applications and benefits are reviewed first individually, and then common combinations of HP-TES systems and their applications are reviewed. Additionally, this paper provides an important contribution to the literature by reviewing the modelling approaches used for TES and HP systems, which are critical for evaluating the efficacy of the different applications. It explores key modelling techniques, their underlying assumptions, and their applicability to different scenarios. The benefits and limitations of each approach are

discussed, along with a review of commonly used software platforms. Hence, this paper presents two key unique contributions to the literature: 1) a comprehensive review of HP-TES coupled systems, and 2) a review of modelling methodologies. By providing a broad and structured overview of available methods, this paper helps researchers and engineers select the most suitable technologies and modelling approaches based on their objectives, system complexity, and computational requirements.

To limit and focus this review, the review does not consider sub-components of HP-TES systems, such as heat-exchanger or working fluid types. Additionally, the review is focussed on the building, rather than district scale. Instead, the review emphasises overall HP-TES system configuration and applications at the building scale. In Section 2, an overview of the TES and HP technology classification and benefits is provided. Then, the categories of TES and HP configuration and their applications are discussed in Section 3. The modelling approaches are discussed in Section 4, while Section 5 includes the conclusions and future perspectives.

2. Background

2.1. Overview of thermal energy storage systems

The operating principle of TES systems is storing heat by charging the storage device and later discharging it to supply heat when needed. It stores thermal energy through processes such as cooling, heating, melting, solidifying, or evaporating materials [34]. TES systems can be grouped into various categories, most commonly, Sensible heat storage (SHS), Latent heat storage (LHS), and Thermochemical heat storage (TCS) according to the means of energy storage [35–37]. A classification of these systems is shown in Fig. 1.

SHS systems store thermal energy by changing the temperature of a material without undergoing a phase change. Compared to LHS and TCS, SHS is more affordable and easier to implement. It commonly uses materials such as water, rock beds, concrete, and molten salts [38], which are widely available and cost-effective. Unlike LHS and TCS, SHS does not rely on complex Phase Change Material (PCM) or chemical reactions, making it simpler to design and construct. However, SHS generally has a lower energy density, requiring larger storage volumes to achieve the same energy capacity as LHS or TCS. SHS systems can be classified by storage medium, including water-based storage, solid thermal mass storage, and molten salt storage [34,39].

SHS materials perform optimally within specific temperature ranges. Water, for example, is effective between 0 °C and 100 °C, while molten salts can operate at temperatures exceeding 1000 °C [38]. Due to its high specific heat capacity, low cost, and chemical stability, water is a preferred storage medium for residential TES applications. Among water-based storage systems, water tanks and aquifer thermal energy

storage (ATES) are two widely used solutions [39,40]. The former is suitable for small-scale applications, such as those used in individual buildings or homes, while the latter is primarily employed in large-scale district heating and cooling networks. Solid thermal mass storage utilizes materials such as rock and metal [39], which can withstand much higher temperatures than water-based systems. These systems are particularly suitable for moderate-temperature applications, such as home air-heating systems or underground heat storage [41]. However, when system temperatures exceed the thermal limits of materials, such as concrete (≈ 400 °C), molten salts become the preferred storage and heat transfer medium due to their high thermal stability and energy capacity [42,43]. Beyond operating temperature range, the capacity and size of the TES container also influence system design, impacting storage efficiency and overall performance [38].

LHS utilizes PCMs to store and release energy through melting and freezing within a specific phase change temperature range. Due to high latent heat capacities of PCMs, LHS systems can significantly reduce the required tank volume and weight compared to SHS, while also offering longer discharge durations and higher energy recovery efficiency [44, 45]. However, challenges such as phase separation, corrosion, low thermal conductivity in the solid phase, and supercooling limit their performance. Additionally, the high production costs of PCMs reduce their feasibility for small-scale domestic applications [23]. LHS systems can be broadly categorized based on PCM composition into organic, inorganic, and eutectic materials [46]. Organic PCMs, such as paraffin and fatty acids, offer chemical and thermal stability, which makes them available across a range of temperatures. Additionally, they are non-corrosive to metals and have high latent heat of fusion. However, organic PCMs are flammable, volatile at high temperatures, and can be expensive. Therefore, considering these characteristics, organic PCMs are suitable for use in low to moderate temperature applications (10–200 °C), including building heating and cooling and solar water heating [22,47]. In comparison, inorganic PCMs, including salt hydrates and metals, provide higher thermal conductivity and lower cost but may suffer from phase segregation and corrosion [48]. They can operate at a wide range of temperatures. For example, salt hydrates are well-suited for low to moderate temperature applications, making them particularly effective for residential heating [49–51]. Metals such as cast iron, steel, and aluminium can withstand high temperatures, making them a suitable choice for industrial waste heat recovery [52,53]. Eutectic PCMs are a mixture of multiple PCMs that melt at a single temperature lower than their individual constituents, offering advantages over single-component PCMs for TES [54]. They demonstrate improved thermal stability, reduced supercooling, and enhanced heat storage density compared to pure PCMs, making them useful for cold storage and solar-thermal power plants [54,55]. However, eutectic PCMs also inherit disadvantages from both organic and inorganic materials, such as low thermal conductivity and poor thermal stability over repeated cycles.

TCS utilizes reversible chemical reactions and physical sorption processes to store heat. Unlike SHS or LHS, TCS achieves significantly higher energy densities by leveraging endothermic and exothermic reactions [56]. This allows for long-term heat storage with minimal losses, as energy is stored in chemical bonds rather than as thermal energy. As a result, TCS systems can store energy at ambient temperature as long as desired without heat losses, making them well-suited for applications requiring seasonal energy storage and efficient heat recovery [57]. However, despite these advantages, TCS faces challenges such as high material costs, complex reaction kinetics, and the need for specialized reactors to facilitate the chemical processes. Additionally, TCS systems often exhibit lower round-trip efficiency due to heat losses, incomplete reaction cycles, and the energy required for material regeneration, which reduces the net energy recovered [58]. Common TCS materials include metal oxides, carbonates, and metal hydrides, each with specific temperature ranges and applications, within the target temperature range between 200 °C and 400 °C [38]. Despite its potential advantages,

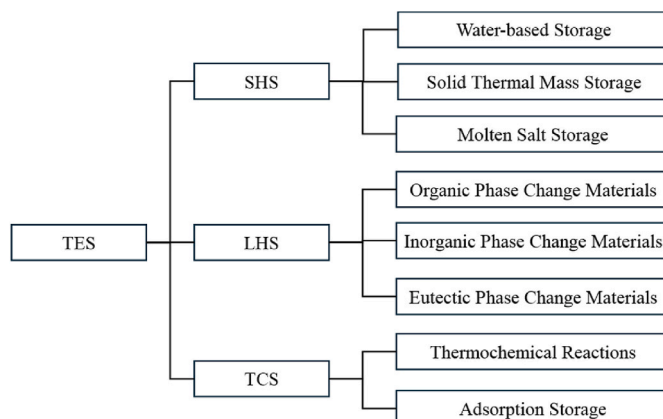


Fig. 1. Classification of TES

TCS technology is still primarily at the laboratory scale, requiring further research to bridge the gap between fundamental studies and large-scale implementation.

2.2. Overview of heat pump systems

HP systems are electrical systems that extract energy from external reservoirs like air or water and converts it into useable heat. The core components of a HP system include a compressor, condenser, evaporator, and expansion valves. These systems operate by circulating refrigerant through alternating stages of compression and expansion, changing it from liquid to vapor and absorbing or expelling heat in the process. Common HP systems on the market include air-source HPs (ASHP), water-source HPs (WSHP) and ground-source HPs (GSHP) [59]. However, with technological advancements and improved economic viability, other types of HP systems are also being adopted in many countries, such as solar-assisted HPs (SAHP) [60–62]. A classification of HP systems by reservoir source and configuration is shown in Fig. 2.

ASHPs extract heat from the outdoor air and transfer it indoors for heating or reverse the process for cooling. ASHPs offer several advantages over other heat pump systems, they are more affordable and easier to install since they do not require underground piping or access to water reticulation system. They are also lighter in weight, making them suitable for installation on walls or rooftops, which is beneficial in space-limited environments. However, ASHPs commonly experience frost on the surfaces of the outdoor coils in cold climates, leading to increased electricity consumption and reduced performance [63]. ASHPs can be classified into air-to-air and air-to-water systems. Air-to-air HPs provide space heating or cooling, transferring heat to the indoor environment through blowers or vents. Air-to-water HPs transfer heat to a water-based system, supplying hot water for radiators, underfloor heating, or domestic hot water applications, making them suitable for both residential and district heating systems [64]. ASHP efficiency is influenced by various factors, including outdoor temperature, thermal loading, and system design. Studies show that ASHP efficiency generally decreases with lower outdoor temperatures [65]. However, the COP can be improved by optimizing circulation water temperature differences and flow rates, with large temperature differences and small flow rates showing 6–8 % improvement in system COP [66]. Additionally, combining photovoltaic-thermal (PVT) collectors with ASHPs can also enhance overall system performance with the COP improved by approximately 52 % compared to the ASHP [67,68].

WSHPs utilize environmental water as a heat source or sink, such as lakes, rivers, or subsurface waters to provide heating and cooling for buildings. Compared to ASHPs, WSHPs benefit from the relatively stable temperature of water sources, resulting in higher efficiency, especially in extreme weather. However, WSHPs are limited by the availability of appropriate nearby water sources and may involve regulatory and environmental considerations [69]. WSHPs can be grouped into surface water HPs, which extract heat from lakes, rivers, or ponds [70], or even

waste-water source [16], and GSHPs [71,72], which extract or reject heat through water circulating in buried heat-exchangers or from groundwater. GSHP systems, therefore, can require substantial land area or deep drilling and high installation costs, unlike surface water HP systems which often have easier access to heat sources and hence lower installation costs.

GSHP systems can be further categorized into open-loop and closed-loop [73,74]. Closed-loop GSHPs circulate a heat-transfer fluid through a sealed pipe network. Depending on land availability and installation depth, the pipe networks can be in horizontal, vertical, or slinky coil configurations [74]. Open-loop GSHPs draw groundwater, pass it through a heat exchanger, and then discharge the groundwater back into the environment. Closed-loop GSHPs are more common as open-loop GSHPs can only be used where sufficient suitable groundwater is available [75]. GSHP applications are characterized by their ability to operate in cold climates due to stable and elevated ground temperatures, with applications including residential and commercial space heating and cooling, snow melting, agricultural crop drying, and district heating systems [74,76].

SAHP are hybrid systems that integrate solar collectors with HPs to enhance efficiency in space heating, water heating, and drying applications [77,78]. Performance for SAHP is dependent on ambient conditions like solar irradiation, temperature, humidity, and wind speed [79]. SAHP systems can be categorized into Direct Expansion SAHP (DX-SAHP) and Indirect Expansion SAHP (IDX-SAHP), with various configurations, including serial, parallel, and dual arrangements [80]. Traditionally, SAHPs operated with solar collectors and HPs as separate units, with solar heat being transferred to the HP's working fluid through an intermediate heat exchanger loop [81].

In DX-SAHPs, the solar collectors and HP are integrated into a single unit, with the solar collector serving as the evaporator [82]. This design allows the refrigerant to flow directly through the collectors, where it absorbs solar heat and undergoes a phase change from liquid to gas [83]. By eliminating intermediate heat transfer steps, this configuration reduces heat loss and prevents refrigerant solidification in extremely low ambient temperatures, improving overall system efficiency. Conversely, IDX-SAHPs utilize a separate heat transfer fluid cycle to deliver heat to the evaporator. In this setup, the refrigerant does not flow directly through the solar collector but instead circulates between the solar collector and a thermal storage unit, where the evaporator is located [79].

2.3. Configurations of HP- TES systems

HP- TES systems can be configured in various ways. Figs. 3 and 4 present nominal configurations for HP- TES systems, however other configurations exist [84,85]. Fig. 1 illustrates the series configuration of the HP- TES system for residential space heating, where the HP and TES are connected sequentially. In this setup, the HP's output serves directly as the TES input, enabling continuous charging while supplying heat to

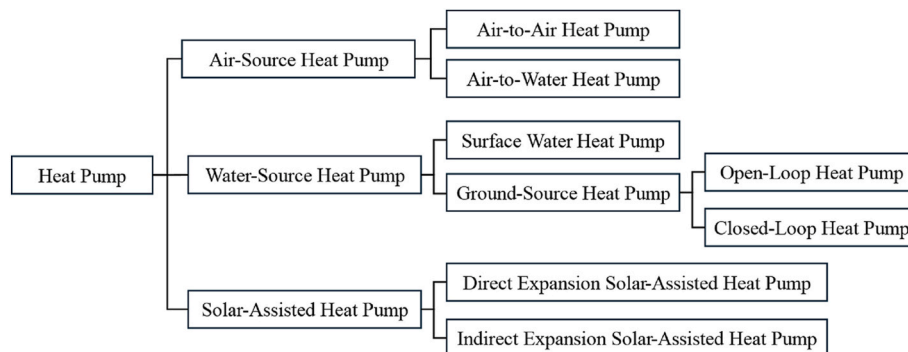


Fig. 2. Classification of heat pumps based on heat source.

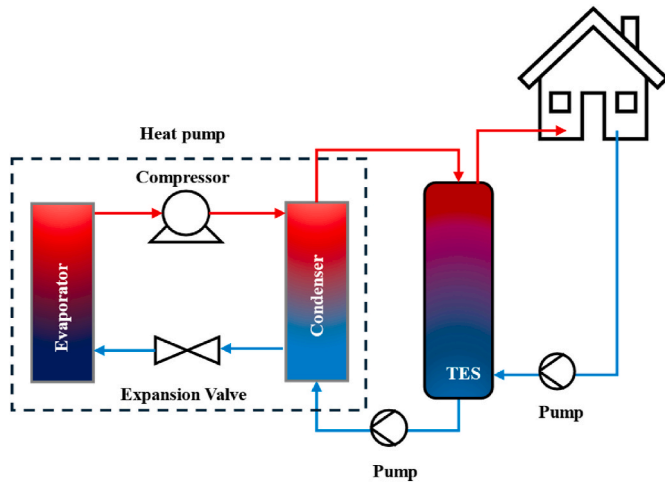


Fig. 3. Series connection between heat pump and thermal energy storage system.

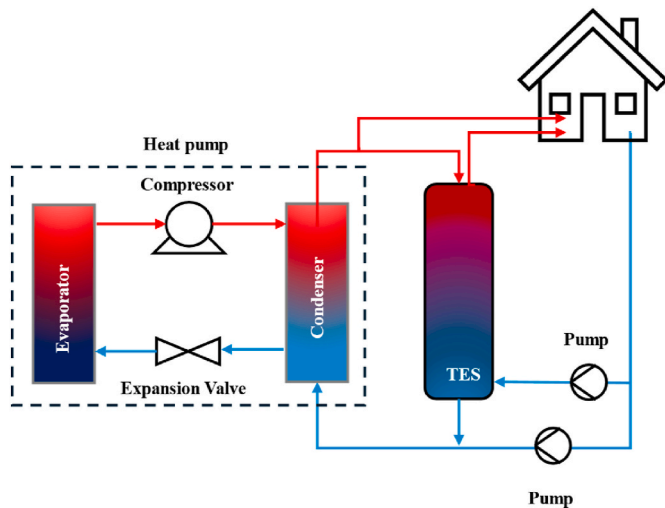


Fig. 4. Parallel connection between heat pump and thermal energy storage system.

the building. In contrast, Fig. 4 depicts the parallel configuration, where the HP and TES operate as independent yet complementary components. In this mode, the HP directly provides heating to the building while simultaneously charging the TES unit when heating demand is low. During peak demand periods, the TES supplements the heating supply, reducing reliance on the HP and improving overall system efficiency.

3. Review of thermal energy storage and heat pump combinations

This section presents common combinations of HP-TES technologies, analysing their benefits, limitations, and applications. A structured approach is adopted to identify relevant studies on TES and HP combinations. Literature is retrieved through keyword-based searches in major academic databases. Search terms included combinations of “thermal energy storage”, “heat pump”, “residential”, “commercial”, “modelling”, and “space heating and cooling”. This review focuses on studies relevant to the integration of TES and HP systems for either residential or commercial applications that are published in peer-reviewed journals or reputable conference proceedings. After screening titles, abstracts, and full texts, a total of 108 studies are selected for in-depth analysis.

3.1. Classification of HP-TES system

HPs coupled with TES systems offer promising solutions for efficient heating and energy management. Various combinations of HP and TES have been studied, including space heating systems with ASHPs and LHS [86], and commercial buildings with SHS tanks and varying loads of HP water heaters [87]. Table 1 summarises representative studies by categorising HP-TES systems based on TES type, HP configuration, and application scenarios.

As shown, one common combination integrates ASHPs with SHS systems, enabling efficient heat storage and discharge for space heating and domestic hot water (DHW) production. In ASHP systems, water storage tanks are widely used to regulate temperature fluctuations and enhance thermal comfort in space heating applications. Wu et al. investigated the air-to-air HPs with a water storage tank for space heating in a single-family house [101], while Le et al. [102] examined air-to-water heat pumps with a water storage tank for DHW production

Table 1
Studies exploring HP-TES systems and their applications.

| Reference | TES Type | HP Type | Scenarios | |
|-----------|---------------|-------------------------------|--|------------------------|
| [88] | Sensible Heat | Stratified water tank | WSHP | TES Sizing |
| [89] | | Stratified water tank | ASHP | Rooftop PVs |
| | | | | Space Cooling |
| | | | | Space Heating |
| | | | | Domestic Hot Water |
| [90] | | Stratified water tank | GSHP | Space Cooling |
| | | | | Space Heating |
| [91] | | Stratified water tank | Water-to-Water HP | Domestic Hot Water |
| [92] | | Aquifer TES | GSHP | Space Cooling |
| | | | | Space Heating |
| [33] | | Fully mixed water tank | Air-to-Water HP | Space Cooling |
| | | | | Space Heating |
| [93] | | Stratified water tank | Air-to-Water HP | Building Energy System |
| [94] | Latent Heat | PCM Storage Tank | Air-to-Air HP | Space Cooling |
| | | | | Space Heating |
| [95] | | Underground PCM tank | Dual-source HP (ambient air or ground) | Space Cooling |
| | | | | Space Heating |
| [96] | | PCM Storage Tank | Air-to-Water HP | Space Heating |
| | | | | Space Heating |
| | | | | Electricity |
| [97] | | Hybrid water-PCM storage tank | ASHP | Domestic Hot Water |
| | | | | Space Heating |
| [98] | | PCM storage tank | Water-to-Air HP | Space Cooling |
| | | | | Space Heating |
| | | | | Domestic Hot Water |
| [99] | | PCM Storage Tank | ASHP | Space Heating |
| | | | | Domestic Hot Water |
| [100] | | PCM Storage Tank | ASHP | Space Heating |

in school buildings. Similarly, Renaldi et al. [31] studied ASHP with water storage tank for residential space heating.

Another combination integrates WSHPs with SHS systems. In this combination, GSHP commonly paired with large water storage tanks or underground TES for year-round heating and cooling. For example, Ryan et al. [90] investigated a GSHP system combined with a stratified water tank for heating and cooling in a large campus. Similarly, Liu et al. [103] proposed a GSHP coupled with a water storage tank to enhance thermal comfort in commercial buildings during summer. Yu et al. [104] explored a GSHP system integrated with soil as a cooling storage medium in China. Additionally, high-capacity SHS systems, such as borehole thermal energy storage [105] or aquifer thermal energy storage [106], have been integrated with WSHPs, making them well-suited for large-scale applications, including district heating and industrial processes.

ASHPs combined with LHS is another widely adopted combination, frequently applied in residential and office buildings. Olympios et al. [107] examined ASHP systems combined with PCM storage tanks for space heating in UK and Germany. Wu et al. [108] studied a cascade ASHP water heater with a PCM storage tank designed for cold climates, demonstrating its effectiveness in improving thermal performance. Similarly, Pelella et al. [109] investigated a multi-source heat pump system include air, solar, and ground source incorporating an ASHP with PCM storage for residential space heating.

WSHPs integrated with LHS, particularly GSHPs combined with PCM storage, represent one of the most widely adopted combinations. Their capacity to store and release thermal energy over extended periods enhances system efficiency and stability. This makes them particularly suitable for buildings with fluctuating heating and cooling demands, such as offices, schools, and hospitals, where consistent thermal comfort and energy efficiency are essential. Benli and Durmus [110] developed a GSHP-PCM latent heat storage system for a university in Turkey for space heating. Zhu et al. [111] examined a GSHP system integrated with PCM cooling storage tank in an office building in China for space cooling.

In conclusion, stratified water tanks are the TES type most widely discussed in literature for both ASHP and GSHP systems in building heating and cooling. LHS using PCM is increasingly explored, particularly in residential and office applications, for improving efficiency under varying load conditions. GSHP systems tend to be applied in larger buildings and campuses, often coupled with high-capacity storage such as aquifers or boreholes.

3.2. Application and impacts of HP-TES systems

This section explores the key applications and impacts of HP-TES systems, highlighting their potential for improving building energy performance while addressing associated challenges. Table 2 summarises the main findings from recent studies.

HP-TES systems provide significant potential for energy savings and peak power demand reductions by optimizing energy use and enhancing demand flexibility. By integrating TES with HPs, HP-TES systems can store heat during off-peak times and utilize it during peak demand, thereby reducing power demand during peak times, and hence also reducing impact on the grid [40,94]. The reported benefits for integrating TES into HP systems are summarised below.

- Improve energy efficiency and decrease peak power demand by optimizing energy use and enabling load shifting
- Minimize frost formation and reduce frequent on-off cycling, thereby extending system lifespan and enhancing operational stability.
- Optimize the size of HP system components and reduce the need for oversized installations.
- Decrease overall system costs through reduced installation expenses and a shorter payback period.

Table 2
Literature on aims and impacts of HP-TES systems.

| Reference | Aims | Impacts |
|-----------|---|---|
| [112] | Increase energy self-sufficiency Reduce grid usage | <ul style="list-style-type: none"> • Achieved a self-consumption rate of 45.2 % and a self-sufficiency rate of 38.6 %. |
| [111] | Reduce and shift peak power demands Reduce cooling and heating costs | <ul style="list-style-type: none"> • Cold TES reduced peak power demands by 45 %. • Hot TES reduced peak electrical demand by 25 %. • Cooling and heating costs reduced by 20 % and 18 %, respectively |
| [95] | Reduce the peak power demand Maintain thermal comfort Reduce the installation cost | <ul style="list-style-type: none"> • Reduced the annual HVAC electricity cost by up to 52 % while saving 45.2 % on electricity consumption. • In the Northern areas, reduced the annual peak load of the HVAC system by 64.9 % |
| [90] | Reduce peak power demand Reduce CO2 emissions Reduce operational cost | <ul style="list-style-type: none"> • Operating costs were reduced by 4.5 % • Peak demands were reduced between 7 and 22 % • Carbon emissions were reduced by over 30 % |
| [98] | Reduce required HP capacity | <ul style="list-style-type: none"> • Ground heat exchanger size was reduced by over 50 % for a cold climate |
| [107] | Reduce operational cost Improve COP over the system lifetime Increase self-sufficiency ratio of electricity | <ul style="list-style-type: none"> • The UK and Germany both achieved annual cost savings of more than 20 % compared to the baseline. • The UK site had a self-sufficiency rate of 34 % and the German site had a self-sufficiency rate of 24 % |
| [113] | Reduce on-off cycles Improve energy efficiency | <ul style="list-style-type: none"> • The number of daily on-off cycles was reduced from 40 to 10 • Saved one-third of electric energy with the same building loads |
| [114] | Reduce peak power demand Optimize HP Size | <ul style="list-style-type: none"> • Peak power demand and total energy requirement of a conventional system reduced by up to 65.4 % and 67.0 % • The borehole length decreased by up to 21.8 % compared to the conventional GSHP system. |

Integrating TES into HP systems enhances system-level flexibility, allowing better alignment between energy supply and demand, and peak demand reductions. Combining TES and HP systems decouples heat production and use; hence, power demand profiles can be optimized, shifting power use for different objectives such as peak demand reduction and power cost reductions by Ref. [115]. Le et al. [116] examined various load-shifting control strategies for a cascade HP coupled with TES, finding that a 3-h peak load shift could be achieved. Furthermore, TES can be added to large HVAC systems to make electricity demand for space conditioning more flexible [10]. Additionally, TES enhances self-utilization, increasing the consumption of on-site renewable energy, increasing energy self-sufficiency, and reducing the dependence on the power network for energy. Studies have shown that HP-TES systems can increase self-consumption of on-site electrical production by 10 % and reduce peak grid exchange hours by 35 % [117]. Kim et al. [118] designed a HP-TES system with various renewable energy generation technologies for space heating, cooling, and DHW production, where TES enables the renewable energy sources to cover 27 % of total heating and cooling energy demand, achieving high self-sufficiency.

Beyond these system-level benefits, TES also improves operational performance at the component level. It allows HPs to operate during more favourable outdoor conditions, allowing reductions in the need for energy intensive defrost cycles. Similarly, the integration of TES can reduce inefficient and lifespan reducing compressor cycling. Finally, the reliance on low-efficiency backup heating systems, such as electric resistive heaters, can be reduced [119]. Overall, the integration of TES into HP systems can increase overall system efficiency and lifespan. Frost accumulation on HP evaporators, particularly in cold climates, can

significantly impact HP performance and increase energy consumption due to frequent defrosting cycles. The integration of TES for defrosting shifts operation to times of more favourable conditions, reducing frost generation, and hence addressing issues such as operational instability, poor defrosting reliability, and deterioration of indoor environments during defrosting cycles [120]. Experimental studies have demonstrated that TES-based defrosting strategies can significantly enhance defrosting performance. For example, one study demonstrated 43.9 % reduction in defrosting period and 7.72 % increase in defrosting efficiency when an energy storage unit was employed, leading to an overall 55.8 % decrease in compressor energy demand [121]. Additionally, TES can reduce the frequency of HP cycling, preventing on-off cycling losses. For residential buildings, properly sized buffer tank storage was shown to reduce HP on-off cycles from 40 to 10 per day and save up to one-third of electric energy consumption [113]. Similarly, TES installation upstream of the HP's brine circulation line can prevent short-cycling operations caused by sudden load fluctuations, leading to a 13 % increase in energy efficiency [122].

Integrating TES with HP systems can reduce the size of key HP components, including compressors and evaporators, leading to lower material costs and improved system efficiency, by sizing components based on peak efficiency rather than peak capacity requirements. By incorporating TES, thermal energy can be stored and used to balance heating and cooling demands, reducing the need for oversized HP components to handle peak loads, allowing for lower capacity compressors and evaporators without compromising system performance [123]. Aljehani et al. [124] demonstrated that incorporating TES could reduce HP compressor size by 50 %. Similarly, integrating HPs with PCMs can potentially reduce the HP capacity requirements by 40–60 % and eliminate the need for auxiliary electric resistance heating in cold climates [125]. Hirschey et al. [123] further investigated the potential of isothermal TES to optimize HP sizing, revealing that the size of the HP system could be reduced by 20 % with the addition of TES. Furthermore, TES enables HPs to be designed with a lower nominal capacity than the peak heating demand, as the TES can supplement during high-demand periods [126].

Integrating TES with HP systems can provide significant economic benefits by operation cost reductions, in addition to reductions in capital expense due to lower capacity requirements. Roth et al. [127] determined the effects of decentralized HPs combined with heat storage of different sizes on the power sector in Germany. The results indicated that even a small buffer storage tank with a 2-h energy capacity enabled HPs to better align electricity consumption with the residual load. This could reduce power system costs by up to 0.9 ct/kWh of provided heat (an approximate 20 % reduction in costs) compared to inflexible HPs. While increasing heat storage capacity further lowers costs, the marginal savings decline as storage size increases. The extent of these savings is limited by electricity pricing structures. Time-of-use (ToU) tariffs play encourage demand shifting to lower-cost periods [128]. For example, HP-TES systems can reduce operational costs by utilizing ToU tariffs to shift electrical loads from peak hours to lower-cost off-peak periods. This approach enhances the cost-competitiveness of HP systems compared to conventional heating systems. Pallonetto et al. [129] evaluated the cost-effectiveness of HP-TES systems combined with different ToU tariffs for a residential building in Ireland. Their findings showed that this approach could reduce annual residential energy costs by 16.5 % while increasing the use of electricity renewable generation. As a result, generation costs for the utility decreased by up to 45.3 %. Similarly, Liu et al. [130] examined the ASHP-TES system in an office building. The results showed that their ASHP-TES system can reduce the annual total cost by 36.35 % compared to the baseline system. However, the economic feasibility of HP-TES systems are influenced by factors such as system scale, electricity pricing structures, and storage efficiency. In some cases, winter tariffs may not provide sufficient incentives for cost savings despite reductions in peak demand [131]. Moreover, in regions where electricity price variations are minimal, the cost-saving potential

of load shifting is significantly constrained.

4. Modelling approach

In practical applications, HP-TES systems are often designed and optimized to meet specific requirements. Therefore, modelling is required to simulate the operation of the system under different technical parameters and operating conditions. This review section excludes intraseasonal TES and district heating from its scope.

4.1. Thermal energy storage modelling

The charging and discharging processes in a TES system involve thermal energy transfer through convection, conduction, and radiation. TES models can be classified into two main categories: Physics-Based Models and Data-Driven Models.

4.1.1. Physics-based models

Physics-based models characterize the behaviour of TES systems by applying the first and second laws of thermodynamics. Various modelling approaches are available. Finite element method (FEM) [132] and finite difference methods (FDM) [133] modelling has been employed to analyse TES systems using solid media, considering thermal properties, geometry, and storage cycles.

One-dimensional stratified tank thermal models are commonly used for water-based SHS systems. They simplify the thermal behaviour of the TES tank into a series of interconnected nodes or control volumes, each representing a discrete layer or section of the tank with its own temperature. One-dimensional thermal models are typically classified into multi-node models and plug-flow models. Since these systems do not involve phase change, the energy balance is based on sensible heat only ("sensible methods"), making them simpler than models that include latent heat effects ("latent methods").

In multi-node sensible models, the storage tank is discretized into a number (n) of interconnected nodes (i) (Fig. 5), each characterised by its

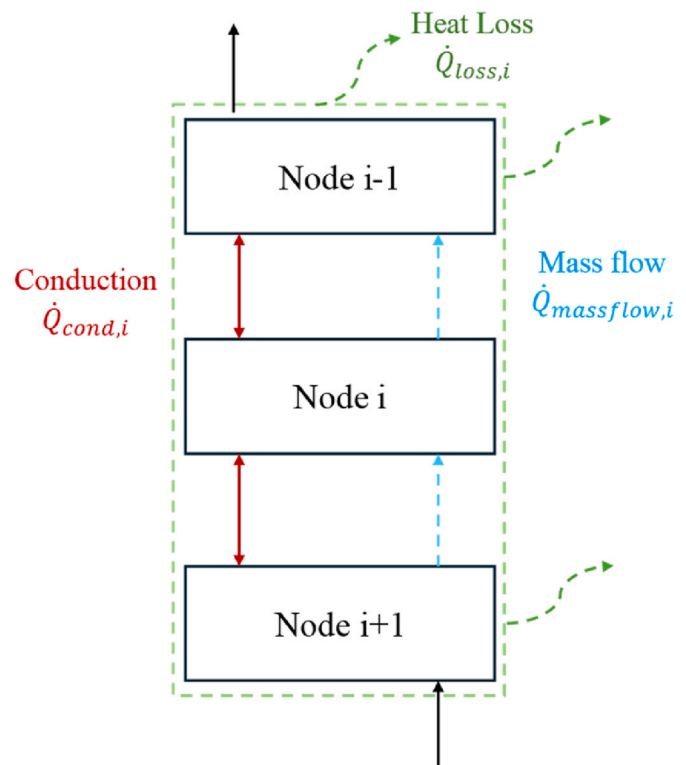


Fig. 5. Heat transfer in multi-node tank models.

area (A_i), temperature (T_i) and diameter (L_i). Heat transfer between neighbouring nodes is modelled using heat transfer coefficients (e.g. convection or conduction) and thermal resistance between nodes is considered. The energy balance at each node is formulated as a system of coupled Ordinary Differential Equations (ODEs) which are solved numerically to model the dynamic behaviour of the system [134].

Heat transfer due to mass flow and thermal losses between each node for the generalised case is shown as follows [135]:

$$\dot{Q}_{\text{loss},i} = U_{\text{tank}} \cdot A_i (T_i - T_{\text{amb}}) \quad (1)$$

$$\dot{Q}_{\text{massflow},i} = \dot{m} \cdot c_p \cdot (T_{i+1} - T_i) \quad (2)$$

Heat transfer due to conduction between each node is shown as follows:

$$\dot{Q}_{\text{cond},i} = k / L_i \cdot A_i (T_{i-1} - T_i) - k / L_i \cdot A_i (T_i - T_{i+1}) \quad (3)$$

The first term is neglected if $i = 1$ (the top of the tank), and the last term is neglected if $i = n$ (the bottom of the tank). k represents the thermal conductivity of fluid.

The energy balance over each node is as follows:

$$m_i \cdot dT_i / dt = \dot{Q}_{\text{massflow},i} + \dot{Q}_{\text{loss},i} + \dot{Q}_{\text{cond},i} \quad (4)$$

The multi-node models offer a balance between accuracy and computational efficiency. It allows for varying levels of detail in temperature distribution by adjusting the number and dimensions of nodes [136]. These models are particularly effective for long-term energy system simulations; however, they may encounter challenges in accurately capturing thermal stratification due to numerical diffusion [137, 138]. To address this, De La Cruz-Loredo et al. [134] developed a hybrid continuous-discrete time model incorporating a moving thermocline barrier to enhance accuracy while maintaining computational efficiency. This approach enables precise tracking of the thermocline position within the tank and accounts for the effects of water transport time delays on temperature distribution. The multi-node approach is versatile, applicable to various tank configurations, including those incorporating internal heat exchangers and auxiliary heaters. However, when employing multi-node models, it is crucial to be mindful of the potential for temperature inversions. To address this, Pate [139] proposed a physical model that effectively captures thermal stratification and predicts inversionary behaviour in both the top and bottom regions of the tank. Additionally, Cadau et al. [136] introduced a flexible multi-node model capable of simulating temperature distributions at varying levels of detail.

Plug flow models classify the fluid into fragments of different sizes and temperatures. The number of fragments and their volume depend on the volume of the tank, the net flow rate of the heat source and load, and the time step used for the simulation [140]. The plug flow model is well-suited for simulating TES tanks under specific conditions, particularly when accounting for temperature distribution in stratified water storage tanks. It can effectively predict temperature profiles by considering factors such as inlet mixing and heat transfer through the tank walls. Rose and Fleischer [141] developed a 1-D Plug Flow numerical model to predict temperature distribution in a stratified water storage tank, accounting for mixing near inlets and heat transfer through tank walls. Similarly, Waluyo [142] created a one-dimensional simulation model for stratified TES tanks, incorporating factors like conduction and mixing effects. However, the accuracy of these models can be limited when fluid turbulence is significant, requiring the inclusion of turbulence models to better align with experimental data. While one-dimensional plug flow models are computationally efficient for building energy simulations, they may lack precision when representing flow-rate-dependent mixing [143].

Latent-heat methods are widely used to simulate PCMs in LHS systems [144]. Where sensible-heat methods are simpler due to predicable

material behaviour, latent methods must consider the complexities and dynamics of phase-change materials. The two most common methods for modelling phase change problems are the enthalpy method and effective heat capacity method [145]. These models effectively handle the complexities of moving boundaries during phase transitions and have been validated against experimental data [146,147]. Wang et al. [148] developed a numerical model based on the enthalpy finite difference method to simulate the LHS tank in a solar GSHP system. The simulation results demonstrated strong agreement with experimental data, validating the model's accuracy in capturing phase change dynamics. Similarly, Susantez [149] employed the enthalpy formulation to address the phase change problem, while Karwacki and Kwidzinski [150] proposed an effective enthalpy approach to track phase transition progression in LHS systems using external measurements, allowing for shape variations. However, the enthalpy analysis based on the first law of thermodynamics is not enough to reveal the LHS thermal behaviours since it does not consider the irreversibility within the system [144]. To address this limitation, exergy analysis, based on the second law of thermodynamics, has been increasingly applied to evaluate the quality of energy storage and identify inefficiencies. Xu et al. [151] established a mathematical model for the exergy efficiency of the charge and discharge processes of a combination of three PCMs and different heat transfer fluids. Carmona et al. [152] developed an integrated energy and exergy model for a water storage tank incorporating cylindrical PCM modules. The model utilizes a multilevel framework combined with the enthalpy method to account for phase change processes. These modelling approaches enable parametric analyses to assess the impact of key design parameters on energy and exergy efficiencies, providing valuable insights for optimizing and designing LHS systems.

4.1.2. Data-driven models

Data-driven methods have gained significant attention in modelling TES systems due to their ability to capture complex, nonlinear relationships from experimental, operational, or simulated data without relying on explicit physical laws. Machine learning (ML) has been used to simulate heat storage performance. Among these approaches, various algorithms have been explored to enhance predictive accuracy and computational efficiency. Artificial neural networks (ANN), support vector machines, and decision trees are commonly used machine learning algorithms. In addition to these advanced techniques, simpler linear models have also been investigated for specific applications where system dynamics can be approximated with lower computational complexity. Linear models have been developed to predict buffer tank temperatures during charging and discharging modes [153]. A research combining numerical modelling and ML for packed bed TES systems demonstrated a 350-fold increase in computational speed while maintaining high accuracy [154]. These approaches provide computationally efficient options compared to traditional system identification methods. For example, ML algorithms, such as Radial Basis Function networks, have demonstrated superior accuracy (90–95 %) compared to conventional physics-based solvers (~60 %) when predicting melt fractions of PCMs, especially during the final stages of melting [155]. Moreover, Kirchsteiger and Daborer-Prado [156] successfully modelled solid sorption-based TES using only five experimental datasets, significantly reducing both experimental time and computational effort compared to simulation models that require solving time- and space-discretized differential equations. However, these methods are limited by their dependence on data quality and the potential for overfitting, where models may perform well on training data but fail to generalize to new conditions [157]. In contrast to physics-based models, which offer a more rigorous and interpretable representation of system behaviour, data-driven models lack the ability to explain underlying thermodynamic principles and drivers of behaviour, which may limit their applicability in certain engineering applications that require transparency and physical understanding [158].

4.2. Heat pump modelling

HP modelling approaches can be categorized into several types. Empirical models and detailed physical-based models including steady-state and dynamic-state models are the main categories.

4.2.1. Physics-based models

Physics-based models are based on the principles of thermodynamics and the laws of conservation. They usually use differential equations to describe the operation of the HP, which characterize key components such as the compressor, condenser, evaporator, and expansion valve [159,160]. Early research on HP systems often employed steady-state models with simplified assumptions to reduce computational complexity, such as neglecting transient effects and simplifying heat transfer mechanisms using algebraic equations derived from thermodynamic relationships. Underwood [161] presented a series of mathematical models for heat pump systems, including steady-state modelling of vapor compression heat pumps. This approach considers each system component individually, providing a comprehensive framework for analysis. Corberan et al. [162] developed a quasi-steady state model to describe the performance of GSHP. Steady-state models are most suitable when system variables remain stable over the relevant time step (ie, react to changes in their input variables very slowly). However, they may introduce inaccuracies, particularly in systems with cyclic behaviour [163].

Dynamic-state models simulate HP transient behaviours and performance at small-time scales, unlike steady-state models which neglect such temporal effects or quasi-steady-state models which simplify such effects. While all physics-based models incorporate mass and energy balances, thermodynamic properties, and component characteristics, dynamic models must be more detailed to capture transient effects. Hence, such models must capture additional characteristics such as thermal inertia [164] to capture the rate of change of key variables over time, additionally, more detailed component representations to capture transient behaviour such as start-up and cycling behaviours [165]. They enable the prediction of key parameters like temperatures, pressures, and mass flows over time at very small-time intervals. FDM [166], finite volume methods (FVM) [167], and FEM [168] are more commonly employed to calculate dynamic performance over other modelling methods. Chi & Didion [169] developed a comprehensive transient model using first-order differential equations to describe heat, mass, and momentum transfer in various HP components. Asghari [170] proposed a simplified heat transfer coefficient model for transient thermal analysis, reducing computation time while maintaining accuracy. Wu et al. [171] established a mathematical model of a water vapor high-temperature HP for analysing the operating characteristics and energy performance of the system. The model includes detailed component models such as the water vapor compressor model with water injection, a plate heat exchanger model, an expansion valve model. The model showed good performance with an average deviation of simulation and experimental results of about 5 %. However, integrating these component-level models into a comprehensive system-level simulation can be a significant challenge. The process is facilitated by using specialized software packages, such as Modelica, TRNSYS, Computational Fluid Dynamics (CFD) and Finite Volume Method (FVM) packages like ANSYS Fluent [172], which provide tools for efficient model development, simulation and analysis. The detailed discussion of using simulation tools to model HP is shown in section 4.3.

4.2.2. Empirical models

Empirical models for HP simulation often rely on manufacturer or experiment data, usually using regression analysis and machine learning methods such as neural networks to learn the performance of HPs from data. Priarone et al. [173] applied the Curve Fit Method in EnergyPlus to model GSHP and air-to-air HPs, demonstrating that HP performance can closely follow manufacturer data with proper input recasting. Simple

polynomial and regression models are suitable when only manufacturer data is available. Bordignon et al. [174] reviewed available manufacturer data and investigated simplified models for predicting heat extraction and rejection, addressing limitations in data availability. However, ANN models perform better when large amounts of measured data are accessible. Park, S.K et al. [175] developed hourly GSHP system performance prediction models using multiple linear regression (MLR) and ANN. The quantitative impact of influencing variables on system performance was analysed with statistical significance. Based on the coefficient of variation of root mean square error (CVRMSE), the prediction accuracy of MLR was 3.56 % and that of ANN was 1.75 %, with no overall bias. Similarly, Xu et al. [176] developed a prediction model based on a GSHP experimental database applied in China. The results showed that the ANN model could provide more accurate predictions for the tested heat transfer rate of GSHP compared with linear and nonlinear regression.

Empirical models are commonly represented as linear or polynomial functions derived through regression analysis of the experimental data [177,178]. These correlations typically consider factors such as fluid temperatures, pressure, and flow rates. Subsequently, energy balance equations are constructed using the derived COP correlation to link the HP's heating or cooling capacity with its electrical power consumption [179]. A simple multiple regression framework will be the bilinear model (Eq.7) and biquadratic model shown (Eq.8) as follows:

$$COP = A + BT_{oc} + CT_{le} + DT_{oc}T_{le} \quad (5)$$

$$COP = A + BT_{oc} + CT_{le} + DT_{oc}T_{le} + ET_{oc}^2 + FT_{le}^2 + GT_{oc}T_{le}^2 + HT_{le}T_{oc}^2 + IT_{oc}^2T_{le}^2 \quad (6)$$

For large-scale HPs, empirical models that rely on real data are particularly valuable for assessing economic and environmental impacts [180]. While manufacturers typically provide COP trends based on ambient temperature, discrepancies often arise between these theoretical values and actual operating performance due to factors such as part-load conditions, system degradation, installation quality, and variations in real-world operating environments. To address this, researchers have developed novel methodologies combining simulation and experimental results to create accurate performance models with minimal experimental data and have proposed modifications to standard correction factors for COP calculations. Bruno et al. [181] found that standard correction factors for COP calculations need modification when storage systems are present. Marchante-Avellaneda et al. [178] introduced a novel two-step methodology for map-based model fitting, integrating simulation and experimental results to minimize experimental costs while maintaining accuracy. This approach is particularly useful for systems with multiple independent variables.

In summary, empirical models offer simplicity and computational efficiency, making them well-suited for rapid estimations and system-level analyses where detailed component behaviour is not a priority. However, their accuracy and applicability are constrained by the need for extensive manufacturer data or experimentally derived performance values, which can be difficult to obtain and may not fully capture variations in real-world operating conditions. While these models facilitate streamlined development, their reliance on predefined data limits their ability to account for transient dynamics, part-load variations, and internal heat losses. For applications requiring greater accuracy and fidelity, models incorporating component-level thermodynamic analyses are essential.

4.3. Summary of heat pump and thermal energy storage modelling approaches

This section summarises the modelling approaches commonly used for HP and TES systems. It aims to support the selection of suitable methods for system analysis and optimization.

4.3.1. HP modelling approaches

HP modelling approaches are summarised as empirical models (performance curve fitting), simplified physics-based models (steady-state), and detailed physical models (dynamic). Empirical models are easy to implement, low-complexity, and have low computational requirements, hence are highly scalable [182,183]. However, empirical models require sufficient performance data to fit performance curves, which may not be available. These models cannot provide insight into HP system operation or design. Additionally, empirical models can produce large errors when applied in non-standard conditions [182].

Simplified physical models are component-level representations that capture the essential thermodynamic and physical behaviour of HP systems without requiring detailed dynamic parameters such as thermal mass. These models typically rely on key component characteristics—such as compressor size and working fluid properties, which can capture steady-state performance and can be used “quasi-statically” to approximate dynamic performance. Simplified models are most efficacious at time-steps where operating conditions remain stable and average performance is of interest [163]. However, these models can lead to significant inaccuracies when systems experience significant transient effects or cycling. Overall, simplified models balance accuracy and model complexity, and are suitable for high level system design, component sizing, and control strategy development.

Detailed physical models are similar to simplified models except they include additional component details required to model transient behaviour and generally provide more complex representations of components, such as efficiency-based compressor models, segmented heat exchanger models, and control volume-based valve models [184]. Thus, dynamic models can capture short-term behaviour such as start-up losses and transient temperature evolution. Detailed physical models are highly accurate and are required for applications requiring fine time resolution and detailed information on component behaviour, especially for HP systems with frequent ON/OFF cycles. These models support system design and simulation of control strategies. However, these models are complex, require longer development times, and more computationally intensive than their simpler counterparts.

4.3.2. TES modelling approaches

TES modelling approaches are categorized into data-driven (empirical) models and physics-based models (sensible and latent). Data-driven models are developed by fitting statistical or machine learning algorithms to measured or simulated data. These models are computationally efficient, eliminate the need for spatial discretization, and can accurately predict tank temperatures during charging and discharging modes when sufficient historical or experimental data are available [153]. The accuracy of data-driven models strongly depends on data quality and representativeness and such models are at risk of over-fitting.

Physics-based models describe TES behaviour based on thermodynamic and heat transfer principles and require physical characteristics and thermodynamic properties as inputs. Sensible methods are used for modelling SHS tanks, focusing on tank sizing and dynamic performance analysis of SHTES systems. Sensible methods can accurately predict charging-discharging times and temperature profiles in SHTES systems, with a trade-off between accuracy and computational efficiency, influenced by the number of spatial nodes and timestep selection. A key challenge in implementing physics-based TES models within system-level simulations is the mismatch of temporal resolution. While system-level models often operate on hourly or sub-hourly time steps, physics-based TES models require much finer time steps on the order of seconds to resolve transient thermal behaviour. This discrepancy significantly impacts model’s computational tractability and accuracy, especially when incorporating long-term storage. To address this challenge, researchers have proposed various approaches. Variable time-step methods, co-simulation techniques, and time series aggregation strategies have been applied to synchronize models with different native

time steps. Variable time-step methods dynamically adjust resolution based on system dynamics, using fine resolution for critical periods or specific subsystems and coarser resolution elsewhere, reducing optimization time while maintaining accuracy [185–187]. Co-simulation frameworks [188,189] allow integration of models with different native time steps by coordinating data exchange between subsystems, though they often require significant implementation effort. Time series aggregation and clustering techniques offer another solution by reducing temporal complexity through the use of representative periods, which is particularly effective for long-term simulations involving seasonal storage [190–192]. These methods can achieve computational speedups of one to three orders of magnitude while preserving accuracy in system-level outcomes.

Latent methods extend sensible methods by incorporating phase change processes, making them suitable for modelling LHTES systems. In addition to the inputs required for sensible methods, latent methods require additional inputs such as melting temperature(s), latent heat of fusion, and phase change kinetics [193,194]. These models provide high accuracy in simulating PCMs in LHTES systems, especially during phase changes, but they increase complexity due to non-linear behaviour at phase boundaries [195]. Furthermore, accurate simulations often demand fine spatial and temporal discretization, increasing computational effort and potentially causing numerical stability issues.

4.4. Integration with simulation tools

Several well-established software packages provide pre-defined components or libraries that can significantly simplify the simulation of TES and HP systems. These tools provide a convenient alternative to developing detailed physical models from scratch, especially when the focus is on system-level interactions rather than the complexity of individual components. Therefore, a large number of studies using software pre-defined models are now emerging. Table 3 summarises the current studies.

TRNSYS, EnergyPlus, and Modelica are widely used tools for modelling TES and HP. These tools include pre-defined components for TES and HP systems and provide comprehensive libraries for simulating various components, which reduces the time required for model development. For example, TRNSYS offers four standard TES models: Type

Table 3
Simulation tool for HP-TES systems.

| Reference | Software | Library/Module |
|-----------|--|--|
| [94] | DOE/ORNL Heat Pump Design Model (HPDM) | HPDM |
| [179] | TRNSYS | HP: Type 1323 TES: Type 1533 |
| [196] | TRNSYS | HP: Type 917 TES: Type 60 |
| [95] | Modelica | HP: Modelica Buildings library TES: DPUTB module |
| [96] | Modelica | Thermocycle library |
| [90] | TRNSYS | HP: Type 581 TES: Type 4 |
| [97] | TRNSYS | HP: Type 941 TES: new component type |
| [98] | TRNSYS | HP: Type 210 TES: Type 215 |
| [197] | Matlab Energyplus | HP: E + PlantComponent object TES: E + PCM TSU object |
| [91] | TRNSYS | HP: Type 927 TES: Type 534 |
| [92] | MATLAB | In-house code written in MATLAB |
| [33] | TRNSYS Python | HP: Type 202 |
| [93] | Modelica | BESMod and AixLib |

60, Type 534, Type 4, and Type 1533. Additionally, Type 581, Type 941, and Type 143 model HPs [90,91,196,198]. Modelica supports various TES technologies [199] and includes AixLib, an open source library that provides a comprehensive framework for modelling TES and HP systems [200]. Similarly, EnergyPlus includes models for modelling water storage tanks, stratification, and heat pumps, enabling accurate predictions of energy use and thermal comfort [173].

The integration of TES and HP systems into these platforms supports multi-objective optimization, such as reducing energy consumption, lowering operational costs, and minimizing greenhouse gas emissions. These capabilities highlight the practical value of commercial tools in both academic research and industrial applications. Shah et al. [201] used TRNSYS optimized a seasonal solar TES system for space heating in cold climates, considering variables such as solar collector area and borehole length. Ferrara and Fabrizio [202] applied Modelica to design and optimize the integration of TES in a solar-assisted ground-source heat pump system. These configurations optimize the combined use of different heat sources, reducing global costs by 34 %. These studies demonstrate that when dealing with complex problems, these tools allow researchers to focus on system-level analysis and optimization rather than low-level component modelling. Furthermore, the algorithms embedded in commercial software have been extensively tested against experimental data, enhancing the reliability and credibility of the research findings. TRNSYS models have accurately predicted both short-term and long-term behaviour of ground source HP systems [203]. Similarly, a TRNSYS model for a building with ground source HP and PCM-based TES has been developed and validated [204]. Modelica, along with other simulation platforms like COMSOL and MATLAB, has been used to compare different TES models, showing good agreement after thorough review [205]. These validated models enable researchers to test design modifications and optimization strategies without physical implementation.

However, reliance on commercial software poses some challenges. The high cost of licences for these software packages is an obstacle to be considered. Furthermore, the availability of components or modules provided by those packages may not align with the research objectives, thus limiting the scope of the research. For example, stratified tank models in commercial software might oversimplify heat transfer mechanisms or fail to account for real-world operational complexities such as mixing or thermal losses [206]. In addition, the “black box” nature of some pre-defined models poses a challenge to the transparency and understanding of modelling methods and theories. While these models often produce accurate results, their underlying equations and assumptions are often lacking visibility, making it difficult for users to critically assess their limitations or adapt them to specific research questions.

In contrast, open-source tools have become increasingly valuable due to their flexibility and transparency. Python-based libraries, coupled with simulation engines like EnergyPlus, enable researchers to develop customized models for specific system configurations [207]. Python provides a comprehensive ecosystem of open-source scientific computing packages. “CoolProp” enables accurate thermophysical property calculations essential for HP cycle modelling and TES material characterisation [208]. The “TESPy” package offers a flexible toolkit for simulating thermal engineering systems, including power plants and HPs [209]. Python-based open-source module “VCCmodelling” has been developed for modelling vapor compression cycles in residential HPs [210]. Additionally, a modular simulation platform for assessing TES integrated with ASHPs has been introduced, incorporating classes for modelling various HP types and TES devices [211]. These tools are highly visible, adaptable, and freely available, however may lack the verification and support of commercial tools, be difficult to integrate into other systems, and require a steeper learning curve and hence extend modelling time.

Addressing these limitations requires a balanced approach that combines the advantages of commercial tools with customisable and

transparent modelling strategies. Future efforts should focus on improving accessibility, increasing model flexibility, and fostering open-source alternatives to support broader innovation in TES and HP modelling research.

5. Conclusion and future perspectives

HP systems coupled with TES are widely used for space heating, cooling, and DHW production. Their ability to reduce peak power demand, lower overall energy consumption, and minimize operational costs has made HP-TES systems a focus of extensive research in recent years. However, there remains a gap in the literature regarding a comprehensive review of HP-TES systems, particularly in terms of their modelling approaches. This paper aims to address this gap by providing a thorough review of HP and TES systems in building heating and cooling. In this paper, categories of HP and TES units were introduced respectively. Then, the configurations of HP and TES and their application were discussed. Each of the HP-TES systems has its own benefits and limitations. Finally, the detailed modelling approaches were presented. Based on the literature analysis, the following conclusions can be drawn.

- (1) TES systems, including SHS, LHS, and TCS. Each offers distinct advantages and limitations. SHS is cost-effective and simple to implement but requires large volumes due to its low energy density. LHS, using PCMs, offers higher energy density and more compact storage, though it faces challenges like phase separation and corrosion. TCS provides the highest energy density with minimal heat losses, making it suitable for long-term storage; however, it remains largely experimental due to high costs and complex reaction requirements.
- (2) HP systems, include ASHP, WSHP, and SAHP. ASHPs are cost-effective and easy to install but have lower efficiency in cold climates. WSHPs and GSHPs provide higher efficiency due to stable water and ground temperatures but require suitable environmental conditions and have higher installation costs. SAHPs enhance performance by integrating solar energy but come with challenges such as weather dependence and a higher initial investment. The selection of an HP system depends on site conditions, cost considerations, and efficiency requirements.
- (3) The common configurations of HP-TES systems include: ASHP-SHS, WSHP-SHS, ASHP-LHS, and WSHP-LHS systems. The selection of an optimal HP-TES combination depends on factors such as climate conditions, energy demand, and budget constraints, requiring careful evaluation to maximize energy efficiency and sustainability.
- (4) The aims and benefits of integrating HP with TES systems include: improving energy efficiency and decreasing peak power demands; minimizing frost formation and reducing frequent on-off cycling; reducing the capacity requirements of HP system components; and decreasing electricity prices by shifting operation time.
- (5) TES system modelling methods can be categorized into physics-based models and data-driven models. Among them, thermal network models are usually used for water-based SHS systems. Enthalpy-based models are widely used to simulate PCMs in LHS systems. Physics-based models provide a rigorous thermodynamic representation. Data-driven models offer efficient predictions but depend on data quality and lack interpretability. The choice of modelling approach should align with the system's design objectives and computational constraints.
- (6) HP modelling approaches can be classified into physics-based models and empirical models. Physical-based models, rooted in thermodynamics, can be further grouped into steady-state models and dynamic models. Empirical models, on the other hand, rely on experimental or manufacturer data, utilizing machine learning

techniques for performance prediction. The choice of modelling approach should be based on the required level of detail and computational constraints, with physical-based models being preferable for high-fidelity simulations and empirical models serving as effective tools for quick estimations.

- (7) Coupling existing modelling approaches with well-established simulation tools to model HP-TES systems provides a new perspective. These tools significantly reduce model development time and allow researchers to focus on system-level optimization rather than detailed component modelling. They also support multi-objective optimization, enhancing energy management, cost reduction, and emissions minimization. While these commercial tools offer reliable and validated results, challenges such as high licensing costs, limited component availability, and a lack of transparency in model structures persist.
- (8) The choice between physics-based and data-driven models for TES depends on the research level, required detail, and performance data availability. Data-driven approaches are more amenable to controller design due to their lower complexity. For components level insights, sensible methods of physics-based models are suitable for SHS and latent methods for LHS can effectively predict temperature during charging and discharging modes when simulate LHS.
- (9) The required level of detail in HP modelling depends on the study objective: the detailed physics-based models are often necessary for technical studies requiring precise performance prediction and functionally required for component level analysis (such as system sizing), whereas general empirical models are sufficient for large-scale energy analysis and policy studies, yet are limited by performance data availability.

According to the summary of current state-of-art technologies for HP-TES systems, the future perspectives can be outlined as follows.

- (1) The development of advanced control algorithms will be crucial for enhancing the performance of HP-TES systems. There is a lack of study on the structure and control optimization of HP-TES systems. These strategies will optimize the operation of HPs and TES in real-time, ensuring that energy storage is synchronized with often difficult to predict energy supply and demand.
- (2) Both empirical and physics-based HP modelling present limitations, due to data availability and complexity. Hybrid models present an opportunity to overcome these limitations. Such models would include physics-based models of the HP system components and utilize the limited available performance data to solve for unknown parameters. Thus, such models could achieve high accuracy, with lower data requirements, and offer the potential to simulate performance under a wide variety of environmental conditions and system configurations.
- (3) Recent research explored optimization strategies for HP-TES systems across various configurations in order to save energy and cost. Although there is a few research for assessing the optimal size and configurations of TES in HP systems, a more comprehensive approach is needed to address varying operational conditions and system requirements. Future research should focus on developing flexible design frameworks that integrate optimization techniques, enabling designers to optimize component sizing, system layout, and control strategies across diverse applications without relying on simulation tools.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT to verify the grammar. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the

content of the published article.

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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