Perspective

Solar Hot Water Systems Using Latent Heat Thermal Energy Storage: Perspectives and Challenges

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Abstract: Domestic water heating accounts for 15% to 27% of the total energy consumption in buildings in Australia. Over the past two decades, the latent heat thermal energy storage (LHTES) system has been widely investigated as a way to reduce fossil fuel consumption and increase the share of renewable energy in solar water heating. However, the research has concentrated on the geometric optimisation of the LHTES heat exchanger for the past few years, and this might not be sufficient for commercialisation. Moreover, recent review papers mainly discussed the development of a particular heat-transfer improvement technique. This paper presents perspectives on various solar hot water systems using LHTES to shift focus to on-demand performance studies, as well as structure optimisation studies for faster commercialisation. Future challenges are also discussed. Since the topic is an active area of research, this paper focuses on references that showcase the overall performance of LHTES-assisted solar hot water systems and cannot include all published work in the discussion. This perspective paper provides directional insights to researchers for developing an energy-efficient solar hot water system using LHTES.

Keywords: heat pipe; latent heat thermal energy storage; phase-change material; NEPCM; solar energy; solar water heating

1. Introduction

Population growth and rapid industrialisation have substantially increased the global energy demand, as well as greenhouse gas emissions. To counter this and reduce dependence on fossil-fuel-powered sources, it has now become essential to adopt renewable energy resources. However, intermittent behaviour and dilute form are key challenges to their successful utilisation. Energy storage could solve these problems and smoothen the operation of end-user applications. One such application is solar water heating, where thermal energy storage can bridge the gap between the energy supply and demand. Extensive research has been conducted on thermal energy storage technologies over the last two decades to improve their energy efficiency. Based on the working principle, thermal energy storage is classified into (i) sensible heat storage, (ii) thermochemical heat storage, and (iii) latent heat storage. Among these, the latent heat thermal energy storage (LHTES) system is popular due to its higher energy storage density than the sensible heat storage system [1–3]. Furthermore, the working fluid of the LHTES system, namely phase-change material (PCM), exhibits negligible changes in its chemical and thermal properties after undergoing thousands of thermal cycles. In addition to this, the hot water production cost of a such solar water heater is approximately one-third of that of the electric water heater [4]. A life-cycle assessment showed that the environmental impacts of LHTES-assisted solar water heaters are also very competitive with those of the other heating systems [5]. For these reasons, the topic has become an active area of research for the past two decades. However, it has been noticed that the research has mainly concentrated on the geometric optimisation of the LHTES heat exchanger in recent years. There has still been a lack of

research on overall system performance, although essential for technology commercialisation. Moreover, recent review papers mainly discussed the development of a particular heat-transfer improvement technique [6–8]. Therefore, this paper presents perspectives on various solar hot water systems using LHTES to shift focus back to on-demand performance studies, as well as structure optimisation studies for faster commercialisation.

2. Solar Hot Water Systems Using LHTES

The conventional solar hot water system utilizes a large hot water tank to store thermal energy. This refers to sensible heat storage. However, the LHTES operates on PCM to store thermal energy. During charging, the PCM melts at a constant temperature or within a temperature range, storing the latent heat of fusion. On the other hand, it gets solidified during discharging and releases the stored energy [9]. The broad classification of PCMs is shown in Figure 1. Among all, organic PCMs are widely studied for solar water heating because of their appropriate thermodynamic properties. Furthermore, they are chemically inert, possess a high latent heat, and perform stably without having a supercooling effect. However, their lower thermal conductivity (less than 0.3 W/m·K) limits their energy storage and retrieval performances. Therefore, different configurations have been developed to effectively store solar energy. These include the following: (i) a heat-pipe-assisted LHTES system, (ii) LHTES modules integrated into the water tank, and (iii) a water storage tank with a separate LHTES tank. The perspectives on each storage system are discussed in the following subsections.
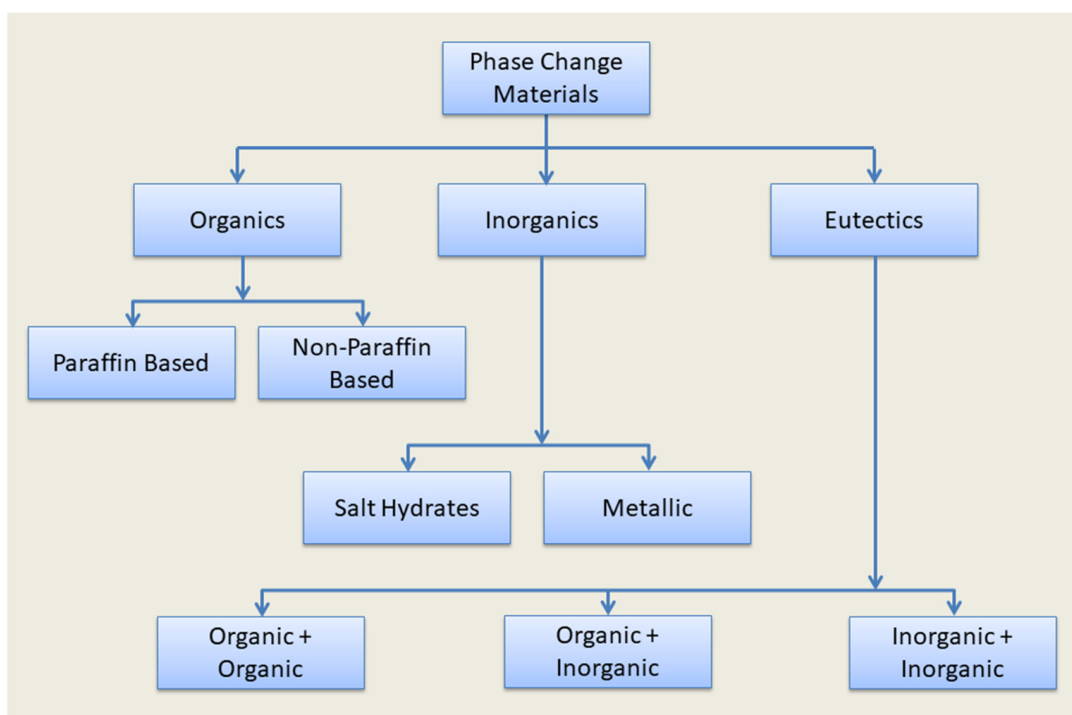

Figure 1. The broad classification of PCMs.

2.1. Heat-Pipe-Assisted LHTES System

In this type of system, a heat pipe is used to transfer collected solar energy from solar collectors to the LHTES tank, as shown in Figure 2. The PCM is filled inside the LHTES tank at the condenser section of the heat pipe. Abhat [10] found that a finned heat pipe inserted into an LHTES is capable of operating within smaller temperature gradients (<10 °C). Liu et al. [11] concluded that the heat-pipe heat exchanger with LHTES can perform the functions of simultaneous charging/discharging for the continuous operation of the system. Analytically, Naghavi et al. [12] showed that integrating the evacuated tube

heat pipe solar collector (ETHPSC) with LHTES can effectively control the overloading of the heat pipe and prevent overheating of the water supply during peak solar radiation hours. According to Lee et al. [13], a two-phase closed thermosyphon system with LHTES can make the storage tank lighter compared to traditional heating systems. Furthermore, the charging and discharging efficiencies were 30% and 17% higher while using PCM than using water.
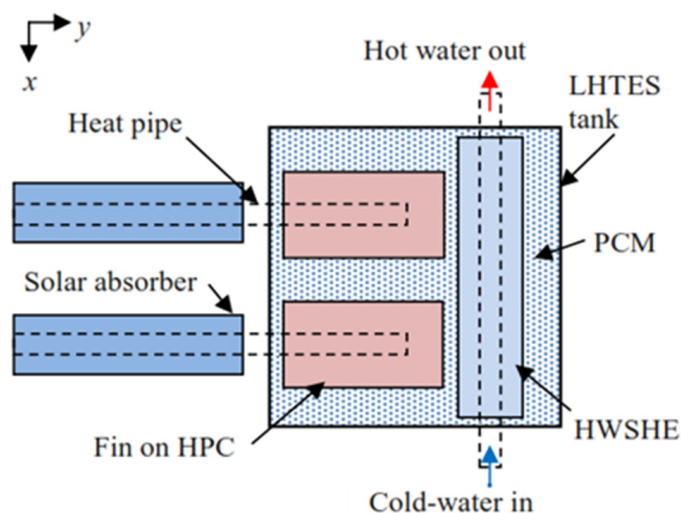

Figure 2. The ETHPSC-assisted LHTES system studied in [14].

The above studies showed that a heat-pipe-assisted LHTES could meet the solar hot water system's requirements and improve the structural design and thermal performance in comparison to the conventional system. Thereafter, many researchers attempted to enhance the thermal performance of such systems by using multiple heat pipes, fins, and different PCMs. Brahim et al. [15] achieved a modest improvement by adding fins to the condenser region of the heat pipes, as illustrated in Figure 3. Numerically, Tiari et al. [16] found that increasing the number of heat pipes improves the thermal performance through increasing the melting rate and decreasing the base wall temperature, while increasing the fin length results in a more uniform temperature distribution within the PCM in the container. Robak et al. [17] experimentally concluded that fins are not as effective as heat pipes in improving thermal performance. Regarding the hot water production capability, Naghavi et al. [14] theoretically extended the operating time for 3 to 4 h with an outlet water temperature of 39 °C. The authors used an array of ETHPSC connected to a common manifold filled with PCM, as shown in Figure 4. However, the thermal performance was higher than the conventional heating system only for a water flow rate higher than 55 L/h. Another analytical study by Bazri et al. [18] reported that the ETHPSC integrated with the PCM with a melting temperature of 56 °C can provide hot water at a temperature of 46 °C for 4 h, with a flow rate of 50 L/h. Based on the theoretical findings, Naghavi et al. [19] designed and fabricated a compact solar water heating system (Figure 5) to conduct experimental tests in charging and discharging modes under real ambient conditions in Malaysia. The system exhibited a thermal efficiency of 38–42% on sunny days and 34–36% on cloudy/rainy days. The on-demand performance study from the same research group showed that the system can effectively provide households with hot water in a tropical climate territory such as Malaysia. With a collector area of 2 m², the system can deliver a minimum of 112–170 L of hot water per day in the worst weather conditions [20].

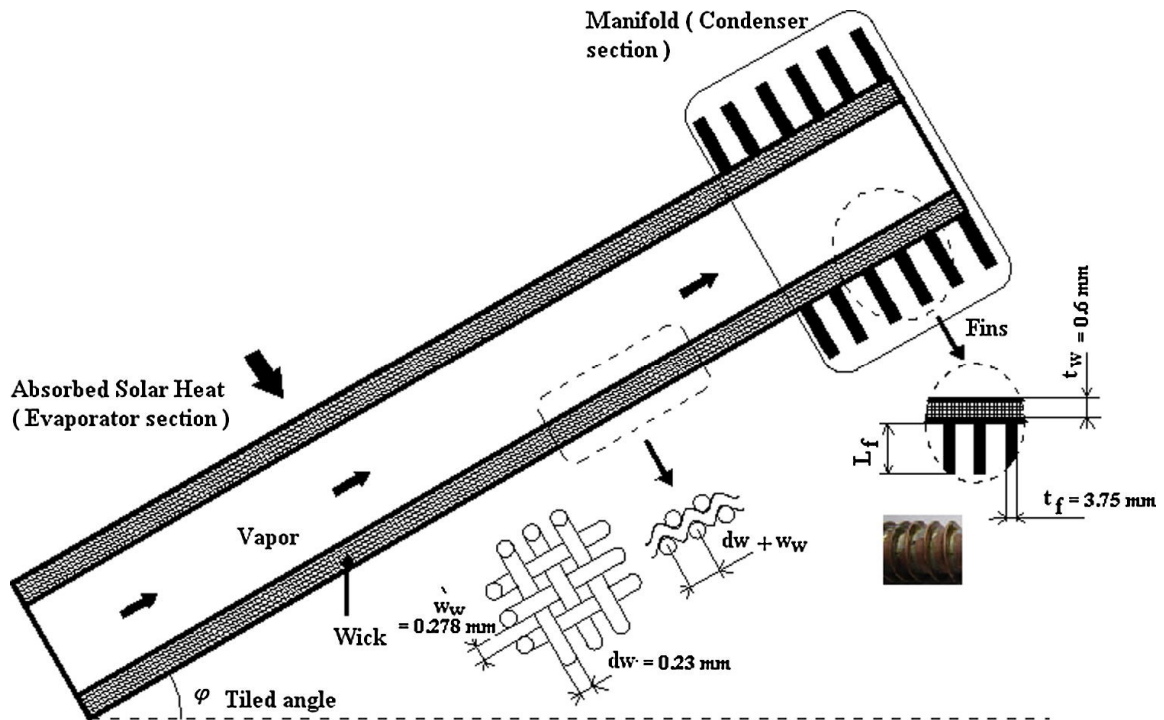**Figure 3.** A detailed description of the heat pipe studied by Brahim et al. [15].
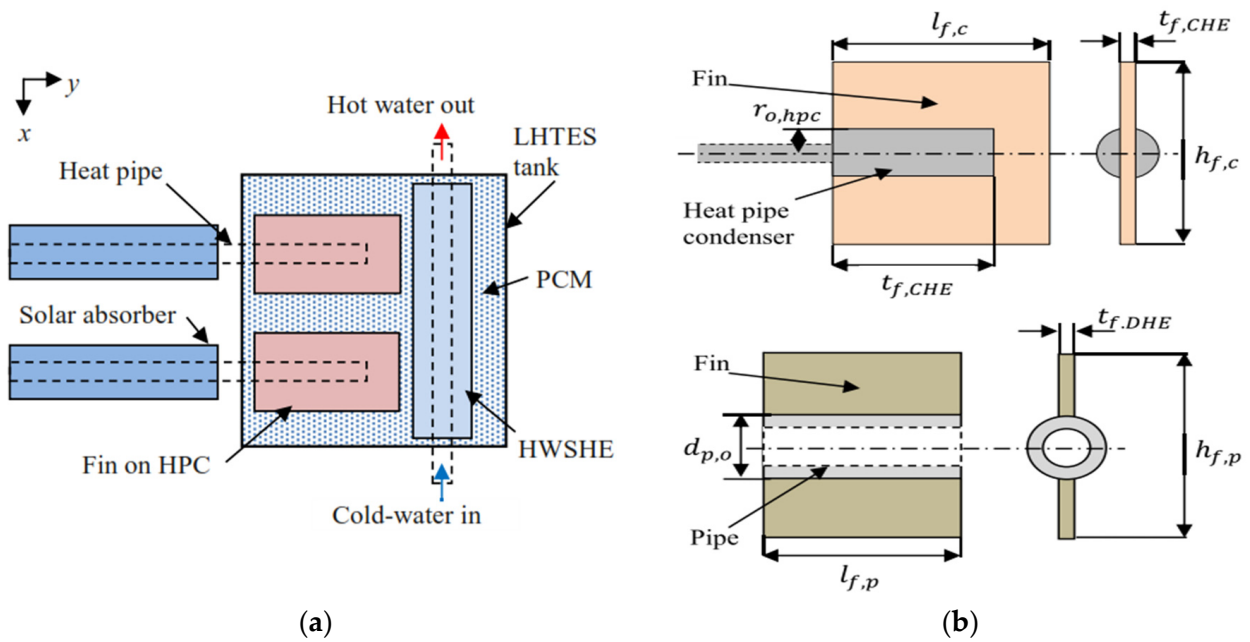

(**a**)   (**b**)

Figure 4. (**a**) ETHPSC-LHTES system studied in [14]; (**b**) fin design for condenser section (**top**) and water pipe (**bottom**).

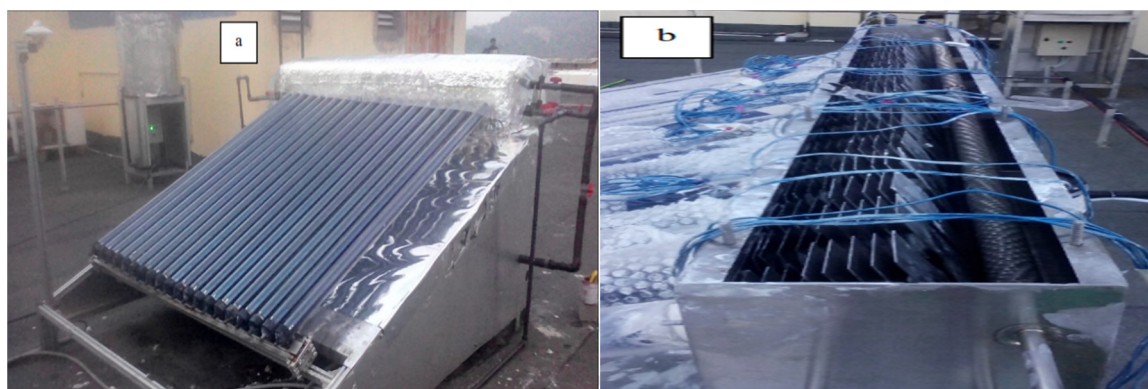**Figure 5.** (**a**) ETHPSC-LHTES experimental system. (**b**) Photo of inside of the LHTES tank [19].

Researchers also studied another type of heat-pipe-based system in which the PCM is filled inside the collector tube, as shown in Figure 6. Papadimitratos et al. [21] improved system efficiency by 26% during normal operation and 66% during stagnation mode when using PCMs compared to a traditional system without PCMs. Through computational fluid dynamics (CFD), Pawar and Sobhansarbandi [22] confirmed that the PCM filled inside the collector tube extends the system operation for a longer period when solar radiation is not available. Wu et al. [23] proposed a novel composite PCM with two phase-change temperatures to accomplish the seasonal variations. In contrast to the above studies, Xue [24] found that the performance of a domestic water heater using PCM-based solar collector is inferior to that of a traditional solar collector due to the low thermal conductivity and high viscosity of the PCM. A summary of heat-pipe-assisted LHTES systems is presented in Table 1.
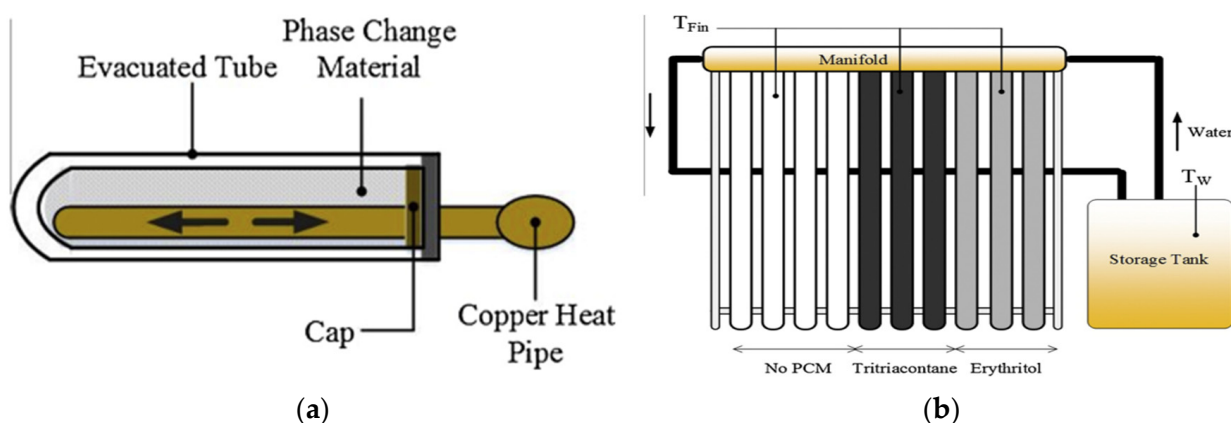

Figure 6. (**a**) Usage of PCM inside the solar collector and (**b**) configuration of examined heat-pipe-based LHTES system in [21].

Table 1. Summary of the literature on heat-pipe-assisted LHTES systems.

Reference	Examined System/Scope of the Study	Type of Study	Observations
Abhat [10]	A finned-heat-pipe-assisted LHTES system.	Experimental	The system was able to operate within smaller temperature gradients (<10 °C).
Liu et al. [11]	A heat-pipe heat exchanger with latent heat storage.	Experimental	The system was able to perform simultaneous charging/discharging for the continuous operation of the system.
Naghavi et al. [12]	The ETHPSC assisted LHTES system.	Numerical	The system was able to control the overloading of the heat pipe and prevent overheating of the water supply during peak solar radiation hours.

Table 1. *Cont.*

Reference	Examined System/Scope of the Study	Type of Study	Observations
Lee et al. [13]	A two-phase closed thermosyphon system with LHTES.	Experimental	The usage of PCM could make the storage tank lighter than traditional heating systems.
Brahim et al. [15]	A plate-screen-meshes-heat-pipe-assisted solar water heater.	Numerical and Experimental	It achieved a collector efficiency of 60% by adding fins to the condenser region of the heat pipes.
Tiari et al. [16]	A finned-heat-pipe-assisted LHTES system.	Numerical	An increasing number of heat pipes improved the thermal performance by increasing the melting rate.
Robak et al. [17]	Different combinations of the heat pipe and fins in the LHTES system.	Experimental	Fins were not as effective as heat pipes in improving thermal performance.
Naghavi et al. [14]	The ETHPSC-assisted LHTES system.	Numerical	Extended the operating time for 3 to 4 h with an outlet water temperature of 39 °C.
Bazri et al. [18]	The ETHPSC-assisted LHTES system.	Numerical	The system was able to provide hot water at a temperature of 46 °C for 4 h, with a flow rate of 50 L/h.
Naghavi et al. [19]	The ETHPSC-assisted LHTES system.	Experimental	It achieved a thermal efficiency of 38–42% on sunny days and 34–36% on cloudy/rainy days.
Naghavi et al. [20]	On-demand performance study of the ETHPSC-assisted LHTES system.	Experimental	The system was able to deliver a minimum of 112–170 L of hot water per day in the worst weather conditions.

2.2. LHTES Modules Integrated into the Water Storage Tank

In this type of system, small PCM containers of various shapes, such as cylindrical, spherical, etc., are placed inside the hot water tank, as shown in Figure 7. During the day, the PCM melts and lowers the temperature of the storage tank. Thus, it prevents the overheating of water and reduces heat losses to the environment.

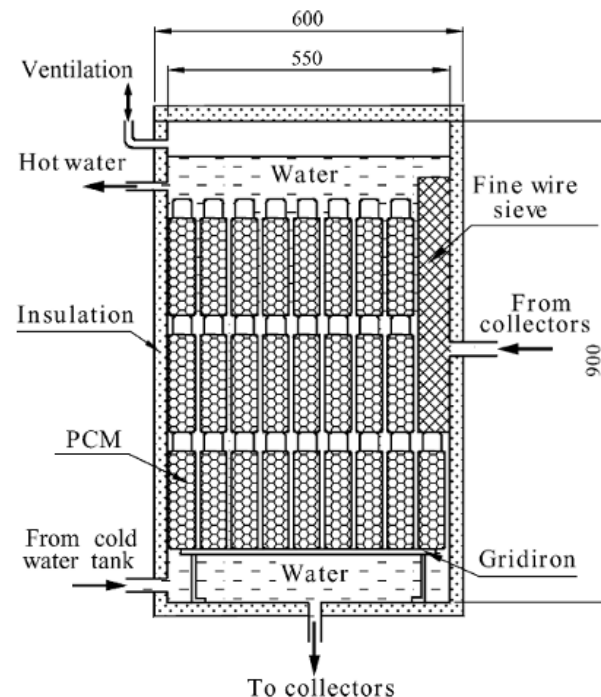**Figure 7.** The PCM modules placed inside the hot water storage tank [25].

A thermodynamic comparison between a solar hot water system with and without a PCM (Figure 7) revealed that the water temperature at the middle of the storage tank decreases consistently during the day until the melting point (48.5 °C) of the PCM is reached. After the intensity of solar radiation decreases, the water temperature remains

constant at 45 °C for approximately 10 h. However, the authors did not consider the drawing of hot water during this period [25].

Mazman et al. [26] added cylindrical-shaped PCM units at the top of the storage tank and observed a good storage density and lower heat losses in the top layer. The efficiency was around 74%. During discharge, the average temperature of the storage tank dropped below the PCM melting temperature range (49–53 °C) within 6–12 h. Al-Hinti et al. [27] placed the PCM-filled aluminium bottles on two levels, as seen in Figure 8. The water temperature was maintained at 13–14 °C higher than the system without a PCM. Wu and Fang [28] used spherical PCM containers and theoretically observed different temperatures at different sections of the storage tank. Experimentally, Fazilati and Alemrajabi [29] utilized PCM-containing spherical capsules in the jacketed shell-type storage tank of the solar hot water system. The energy storage density and the exergy efficiency were improved by up to 39% and 16%, respectively. Moreover, the system could supply hot water at a specified temperature for a 25% longer time. Navarro et al. [30] incorporated PCM-containing high-density polyethylene spheres into a storage tank and reported the undesired results of PCM leakage in the laboratory, as illustrated in Figure 9. Therefore, it was recommended that the PCM spheres must be thermally cycled and cleaned before implementing in the real application of domestic hot water. Similarly, Fang et al. [31] designed a microencapsulated phase-change material (MEPCM)-based LHTES system and found that the higher MEPCM particle fraction and higher PCM core fraction result in a higher energy storage capacity. However, it slowed down the energy storage rate. Overall, the system exhibited a stable operation and a high heat transfer rate, indicating that it is practical for use in domestic hot water systems.
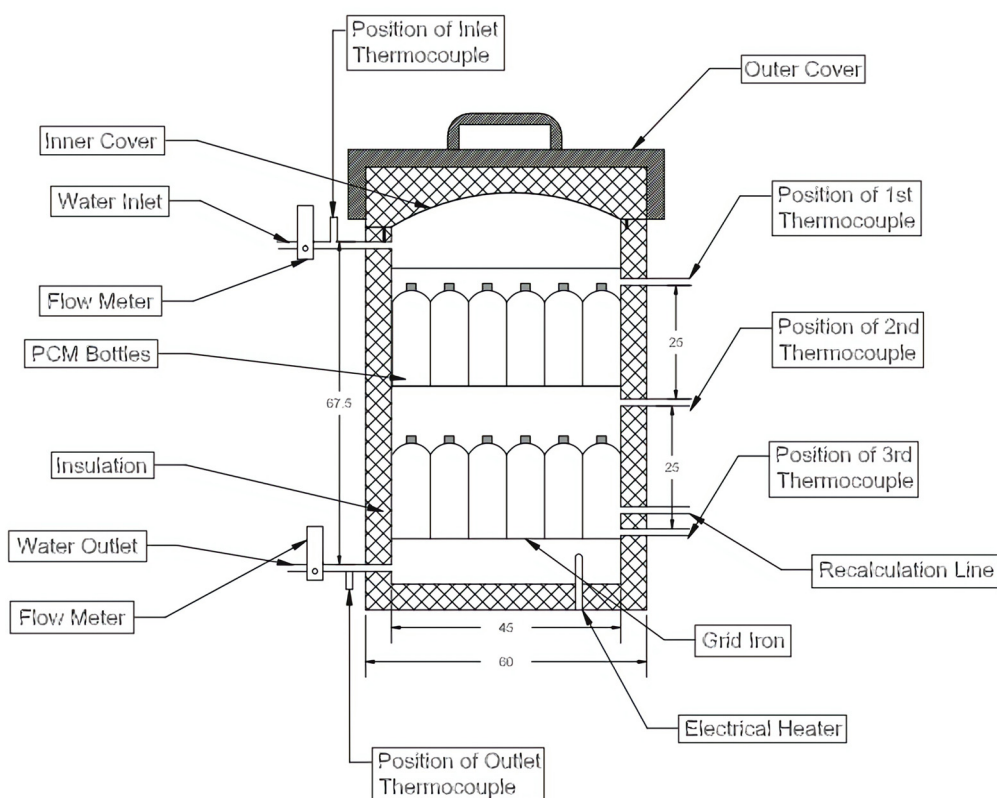

Figure 8. Schematic cross-sectional view of the cylindrical PCM units inside the hot water storage tank [27].

Figure 9. The PCM spheres after the tests in the experimental setup [30].

Researchers also studied the effects of various key parameters such as the type of PCM, its location inside the tank, the tank's volume, etc. Nkwetta et al. [32] confirmed that the top position of the PCM was better than the middle position. It was noticed that the improvement in the solar fraction through integrating PCM modules depended on the tank volume [33]. Studies on different PCMs reported that the storage-tank volume can be reduced by more than 50% by using multiple hybrid storage tanks [34]. An investigation into the storage tank's aspect ratios revealed that a higher aspect ratio (3:1) degraded the charging performance, unlike sensible storage tanks (Figure 10). Therefore, a lower aspect ratio (1:1) should be preferred for hybrid thermal storage with PCM spheres [35]. Bayomy et al. [36] demonstrated that the storage efficiency of the LHTES system was closely linked to the user's hot water demand.

Apart from these studies, research was also carried out on different shaped containers and configurations. Numerically, Elbahjaoui and Qarnia [37] investigated the rectangular LHTES (Figure 11) integrated with solar collectors and observed the outlet water temperature in the range of 43.6–24 °C, 51.7–24 °C, and 62.86–24 °C, respectively, for RT42, RT50, and RT60 during discharging. Abdelsalam et al. [38] examined direct and indirect heat-exchange modes in the water storage tank and hybrid storage (water + PCM modules) tanks, as depicted in Figure 12. The direct mode operated with a higher solar fraction than the indirect mode due to thermal stratification. To further improve the system, the authors suggest carefully selecting the melting temperature to optimize latent heat storage, which will minimize temperature fluctuations within the system. Kılıçkap et al. [39] developed an LHTES system that was integrated with a hot water collector and tested it under Elazığ climatic conditions (Figure 13). The highest thermal efficiency, namely 58%, was achieved in July when a PCM was used in the storage tank. Moreover, the system with PCM was able to transfer stored heat to water at night, providing hot water for an additional 1–1.5 h.
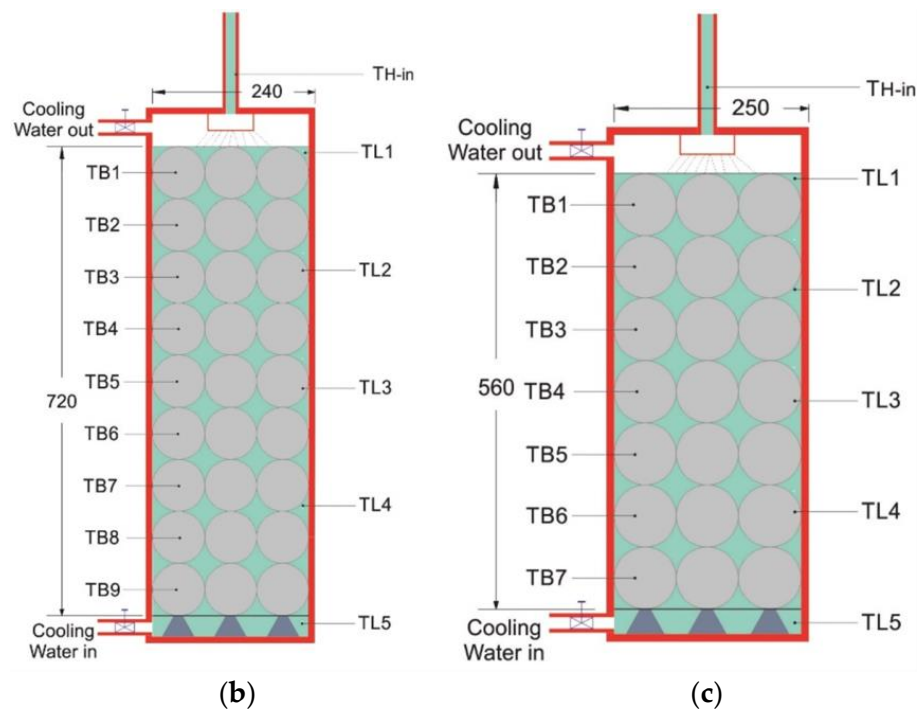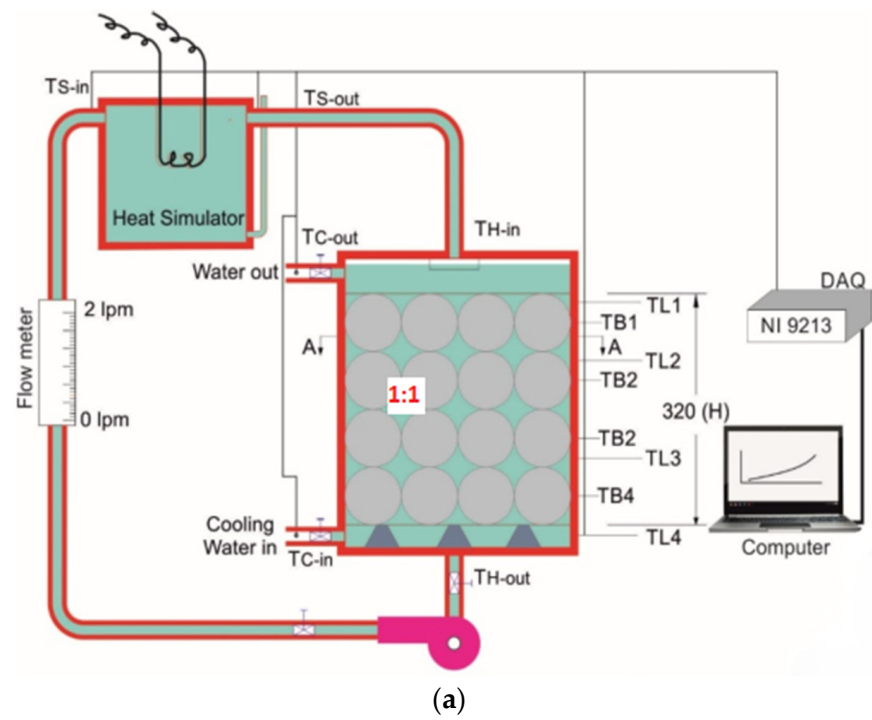
Figure 10. The layout of the storage tanks with an aspect ratio of (**a**) 1:1, (**b**) 3:1, and (**c**) 2:1 [35].
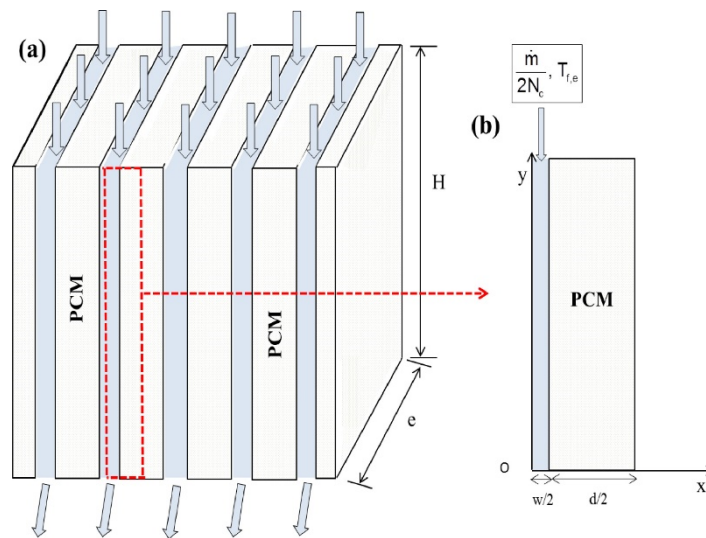
Figure 11. Schematic of (**a**) the storage unit and (**b**) the symmetric computational domain studied in [37].
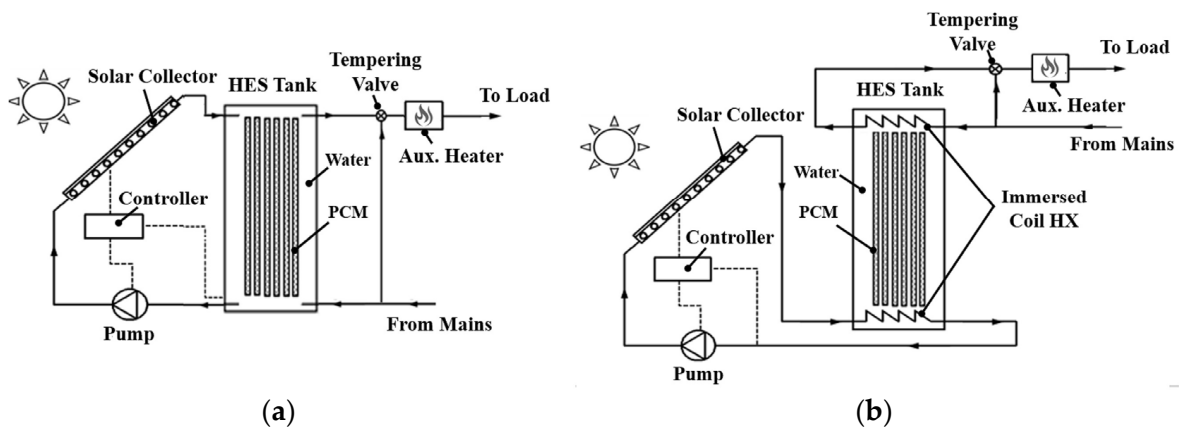
Figure 12. Schematic diagram of (**a**) direct heat exchange mode and (**b**) indirect heat exchange mode [38].

Figure 13. The LHTES studied by Kılıçkap et al. [39].

Contradictory to the above findings, some authors have also reported undesirable results. The simulation study by Kousksou et al. [40] confirmed that the use of PCMs might not be beneficial, as previously found by Talmatsky and Kribus [41]. The authors suggested that the choice of the PCM must be performed on a case-by-case basis depending on the precise location of the installation. De Gracial et al. [42] extended the work of Farid and Stretton [43] to validate the previous outcomes and explained the benefits of PCM in the storage tank. However, the storage volume of the hot water was reduced from 180 to 123 L due to the incorporation of 57 PCM-filled tubes. The system with many small tubes could provide hot water for a longer time during the first discharge but a limited time in other discharges. A summary of the usage of LHTES modules inside the water storage tank is presented in Table 2.

Table 2. Summary of the literature on the usage of LHTES modules inside the water storage tank.

Reference	Examined System/Scope of the Study	Type of Study	Observations
Canbazoğlu et al. [25]	Placed cylindrical LHTES modules inside the hot water tank.	Experimental	The water temperature remained constant at 45 °C for approximately 10 h after the solar radiation decreased.
Mazman et al. [26]	Added cylindrical-shaped PCM units at the top of the storage tank.	Experimental	It achieved a thermal efficiency of 74%. During discharge, the average temperature of the storage tank dropped below the PCM melting temperature range (49–53 °C) within 6–12 h.
Al-Hinti et al. [27]	Placed the PCM-filled aluminium bottles inside the hot water tank.	Experimental	The water temperature was maintained at 13–14 °C higher than the system without PCM.
Fazilati and Alemrajabi [29]	Utilized PCM-contained spherical capsules in the jacketed shell-type storage tank.	Experimental	The system was able to supply hot water at a specified temperature for a 25% longer time.
Fang et al. [31]	Designed a MEPCM-based LHTES system.	Experimental	The system exhibited a stable operation and a high heat transfer rate, indicating that it is practical for use in domestic hot water systems.
Nkwetta et al. [32]	Studied different positions of PCM inside the storage tank.	Numerical	The top position of the PCM was better than the middle position.
Teamah et al. [34]	Studied the combination of different storage tanks with different PCMs.	Numerical	The storage tank volume was reduced by more than 50% by using multiple hybrid storage tanks.
Afshan et al. [35]	Studied different aspect ratios of the hybrid water storage tank.	Experimental	A lower aspect ratio (1:1) was recommended for hybrid thermal storage with PCM spheres.
Elbahjaoui and Qarnia [37]	Rectangular-shaped LHTES with different PCMs.	Numerical	The outlet water temperature was observed in the range of 43.6–24 °C, 51.7–24 °C, and 62.86–24 °C, respectively, for RT42, RT50, and RT60 during discharging.
Kılıçkap et al. [39]	The PCM was filled inside the annulus of the hot water tank.	Experimental	It achieved the highest thermal efficiency of 58% by using PCM. Moreover, the system with PCM was able to transfer stored heat to water at night, providing hot water for an additional 1–1.5 h.

### 2.3. Water Storage Tank with a Separate LHTES

A separate shell-and-tube heat exchanger has been used as an LHTES either alone or with the water storage tank, as shown in Figure 14a. During the daytime, a portion of the hot water coming out from the solar collector is diverted through the LHTES, and the energy gets stored inside the LHTES. During the nighttime, when the water tank's temperature drops below the preset value, the water is circulated via the LHTES to recover the stored energy.
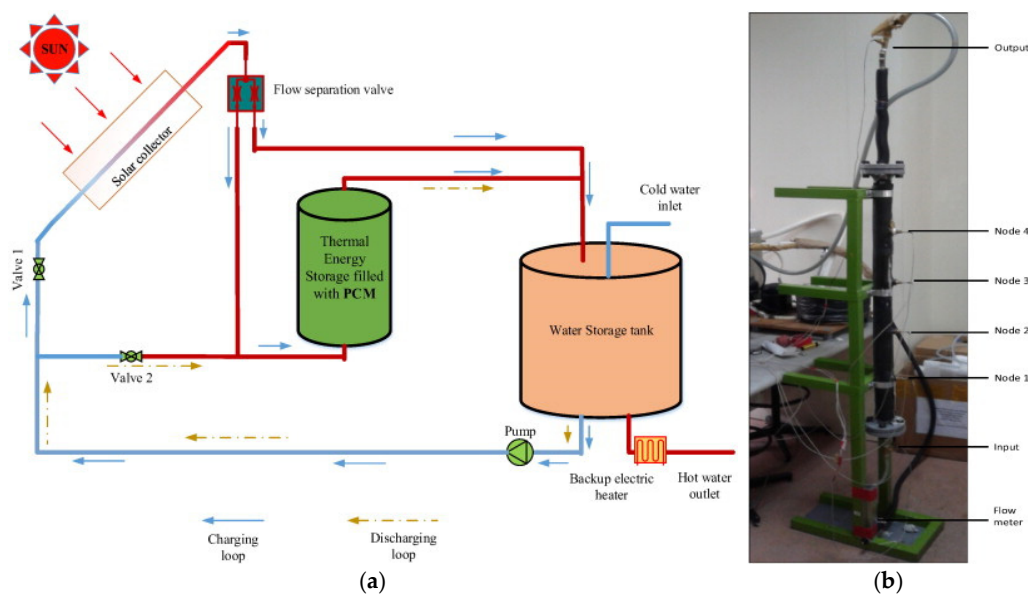
Figure 14. (**a**) Schematic of a solar hot water system with separate LHTES studied in [44] and (**b**) photograph of the LHTES used in [44].

Mahfuz et al. [44] used a vertical shell-and-tube heat exchanger that was 1 m in length as an LHTES (Figure 14b) and filled the annulus with paraffin wax with a melting point of around 56.06 °C. During discharging, the outlet water temperature remained above 40 °C for just 30 min, which was for the lowest flow rate (0.033 L/min). Luu et al. [45] developed a dynamic model of latent heat battery to integrate it with the domestic solar water heating system. The authors found that the proposed tankless system could increase fossil fuel savings by 15.7% more than a conventional system. The same authors theoretically achieved the discharge average temperature of 40 °C by considering various design perspectives of the LHTES system [46]. Lamrani et al. [47] modelled the solar parabolic trough collector with a 100 m^2 area to assist the LHTES system in supplying hot water to a large building. The authors found that the choice of PCM is crucial for maximising the system's performance. Using a PCM with a low melting temperature can result in an inability to provide hot water at the desired temperature, while a PCM with a high melting temperature may not fully utilize available solar energy for storage. The authors recommended paraffin wax RT55 for domestic hot water systems. An experimental study on a spiral-finned heat exchanger using PCM (melting temperature of 52 °C) showed that the system could provide hot water of 40 °C with a flow rate of 0.5 L/min for just 2000 s (0.55 h) [48]. A performance comparison between latent and sensible heat storages using a tube-in-tank heat exchanger demonstrated that the hot water temperature should be emphasized according to phase-change temperature. Furthermore, the system was able to provide hot water of 40 °C with a flow rate of 0.6 L/min for just 19.3 min when the inlet water temperature was 20 °C [49]. Dogkas et al. [50] used a staggered finned heat exchanger (commonly used as an evaporator and condenser in air-conditioning systems) as a thermal storage system and observed that tanks can be charged quickly, in less than 2 h, using either solar energy or a heat pump. In addition, the system was able to produce 106 L of hot water instantly at a temperature above 40 °C during discharging. The capability of a multi-tube heat exchanger (Figure 15) to serve as the LHTES for a solar water heating system was examined by Osman et al. [51]. The results showed that the LHTES unit was able to increase the hot water temperature by 7–12 °C and maintained a constant hot water supply for extended periods of about 2–3 h. Furthermore, natural gas consumption was also reduced by 130 m^3 annually.
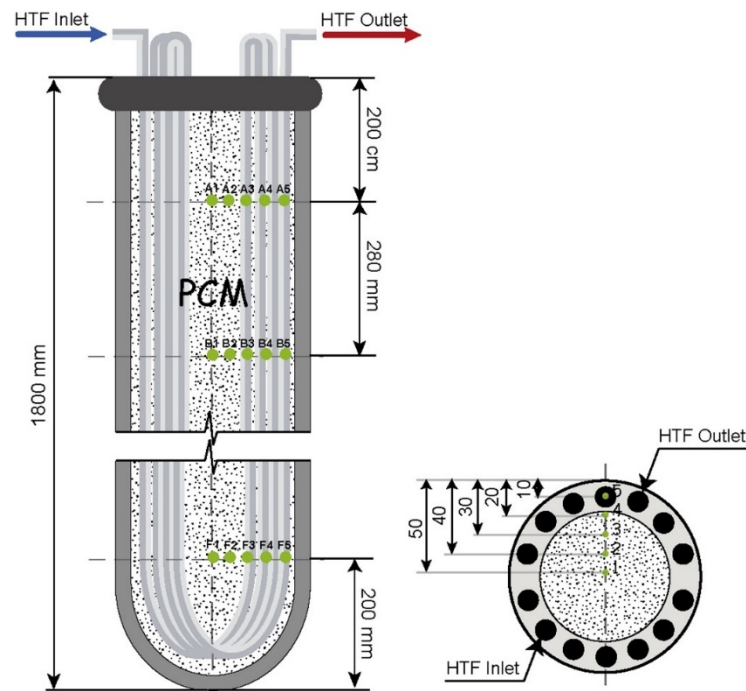
Figure 15. The LHTES studied by Osman et al. [51].

As seen in Figure 16, the series and parallel configurations of the hybrid storage tank were analysed by Huang et al. [52] through TRNSYS software, and the solar fraction of the series system was observed to be 30% and 5–12% higher than a single water tank and parallel configuration, respectively. The authors proposed the use of a PCM with a melting temperature range between 47.5 and 57.5 °C and also optimized the volume ratio of the PCM unit. Shalaby et al. [53] designed a rectangular container with a finned tube bank to use as LHTES with a flat plate solar water heater, as illustrated in Figure 17. The authors divided the PCM into thin slices to improve its thermal conductivity and achieved a daily efficiency of 65% by combining the PCM and water storage tank. This configuration was able to provide hot water at a consistent temperature range of 50–60.4 °C for 24 h.
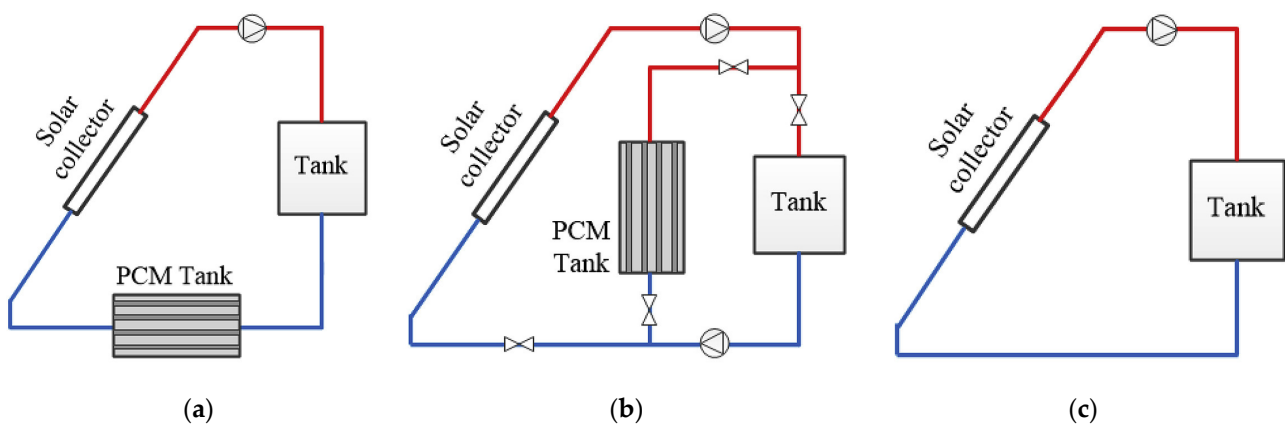

Figure 16. (**a**) Series (**b**) parallel and (**c**) single tank systems examined in [52].
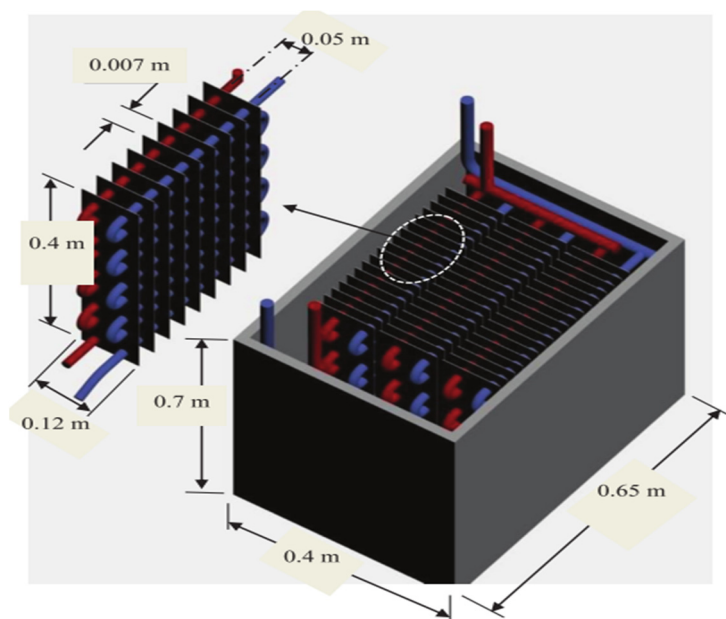
Figure 17. Shell-and-finned tube heat exchanger designed in [53].

A summary of the hot water systems with a separate LHTES unit is presented in Table 3.

Table 3. Summary of the literature on the hot water systems with a separate LHTES unit.

Reference	Examined System/Scope of the Study	Type of Study	Observations
Mahfuz et al. [44]	A shell-and-tube heat exchanger as a separate LHTES system.	Experimental	For the lowest flow rate (0.033 L/min), the outlet water temperature remained above 40 °C for just 30 min.
Luu et al. [45]	A shell-and-tube-type tankless latent heat battery.	Numerical	Improved the fossil fuel saving by 15.7% more than a conventional system.
Luu et al. [46]	A shell-and-tube-type tankless latent heat battery.	Numerical	Achieved the discharge average temperature of 40 °C.
Lamrani et al. [47]	Parabolic-trough-collector-assisted rectangular shell-and-tube-type separate LHTES system.	Numerical	The PCM with a low melting temperature was unable to provide hot water at the desired temperature, while a PCM with a high melting temperature was not able to fully utilize available solar energy for storage.
Lu et al. [48]	A spiral-finned heat-exchanger-type separate LHTES system.	Experimental	The system has provided hot water of 40 °C with a flow rate of 0.5 L/min for just 2000 s (0.55 h).
Gao et al. [49]	A tube-in-tank-type separate LHTES system.	Experimental	The system was able to provide hot water of 40 °C with a flow rate of 0.6 L/min for just 19.3 min.
Dogkas et al. [50]	A staggered finned heat exchanger as a separate LHTES system.	Experimental	The system was able to produce 106 L of hot water instantly at a temperature above 40 °C during discharging.
Osman et al. [51]	A multi-tube heat exchanger as a separate LHTES system.	Numerical and Experimental	The LHTES unit was able to increase hot water temperature by 7–12 °C and maintained a constant hot water supply for extended periods of about 2–3 h.
Shalaby et al. [53]	Rectangular shell-and-finned tube-bank-type heat exchanger as a separate LHTES system.	Experimental	The configuration was able to provide hot water at a consistent temperature range of 50–60.4 °C for 24 h.

3. Current Research Activities (Last 5 Years)

In the last decade, various techniques have been developed to improve the heat transfer rate in the LHTES systems [54] for solar energy applications. This includes investigations into different types of heat exchangers [55–57], different types of shell shapes [58], different angular positions [59,60], multi-tube heat exchangers [61], eccentric tube heat exchangers [62], nanoparticles and porous matrixes [6,63], spiral tube heat exchangers [64,65], cascaded PCM [8], different types of fins [7,66], etc. One of the most popular techniques, incorporating nanoparticles into pure PCM, i.e., nano-enhanced phase-change material (NEPCM), could enhance the thermal conductivity of the PCM and, hence, the overall thermal performance [67]. However, it also affects the other thermodynamic properties and thermal stability of the PCM [68], thus making the operation complicated. Another popular technique, longitudinal fins, is widely investigated because of their low cost and ability to penetrate the dead zone of the annulus [69]. The researcher then put effort into further

optimizing the energy storage/retrieval process in a longitudinal finned LHTES system. This includes studies on different fin parameters [7,70], integration of tube eccentricity with fins [71,72], the combination of fins with multiple heat transfer tubes [73], the insertion of metal foams and nanoparticles [74], the combination of fins and rotation [75,76], usage of optimization methods [77], etc. Recently, research has converged on the innovation of fin designs. This leads to the development of novel fin structures, such as branched fins [78], triangular fins [79], superimposed fins [80], snowflake fins [81], tree-shaped fins [82], honeycomb structured fins [83], punched fins [84], corrugated fins [85], cesaro fins [86], and many more. However, the manufacturing and integration of such complex fin structures seem to be difficult. More importantly, the direction of research on heat-transfer improvement techniques has deviated in recent years. Unfortunately, only a limited number of the aforementioned references discussed the overall system performance of solar hot water systems, which is a crucial aspect to consider. Most studies have investigated a small individual LHTES unit under the fixed heat source temperature rather than focussing on a whole integrated solar hot water system. While working on heat-transfer improvement techniques, researchers also need to keep in mind the system integration and its ability to be commercialised. Therefore, there is a need to work parallelly on both on-demand performance studies and structure-optimisation studies for the commercialisation of such technology.

4. Perspectives and Challenges

From the aforementioned literature, it can be concluded that the PCM-based LHTES system can provide hot water for domestic purposes and improve the share of solar energy in building energy consumption. Each type of system has its advantages and challenges.

(i)   The heat-pipe-assisted LHTES system appears to be a promising solution for domestic hot water supply. Its ability to provide hot water at a temperature of 40–45 °C, at a flow rate of 50 L/h, for an extended period of 3 to 4 h, along with a thermal efficiency between 30% and 50%, and its ability to solve thermal stratification and overheat issues are significant advantages. Furthermore, replacing the conventional hot water tank also reduces the space requirement. These features make the system an attractive option for those looking to integrate sustainable energy solutions into their buildings. However, the high cost of the heat-pipe-based solar collector and a lack of experimental work to prove the system's effectiveness and economics are challenges that need to be addressed. Further research and optimization studies are needed to justify the LHTES applicability and bring down the overall cost of the system.

(ii) The second type of system, which utilizes LHTES modules inside a hot water tank, has the potential to maintain a temperature of 40–55 °C for extended periods, i.e., of 6 to 12 h. However, most studies have not accounted for the hot water withdrawal during the testing. As of now, there is no evidence to suggest that this type of system is superior to the first type, but it does exhibit higher thermal efficiency (50–70%), theoretically. While it cannot fully replace a conventional tank, it has the potential to reduce the size of the tank. One of the biggest challenges in implementing this type of system is the risk of PCM leakage from the small LHTES modules if not thermally cycled before use. Additionally, there are a variety of parameters that govern the system's performance, such as the type of PCM, aspect ratio of the storage tank, position of PCM modules (top, medium, and bottom), storage tank volume, and the number of storage tanks, which make optimization a complex process. Therefore, more on-demand performance studies are needed to optimize hot water production and address the challenges associated with this type of system.

(iii) The third type of system, which utilizes a separate LHTES tank, has not yet reached maturity. Studies have shown that these systems are currently unable to provide hot water at temperatures of 40 °C for even a short period (3–4 h). The major challenges are the formation of a solid layer around the inner tube of the heat exchanger during discharging and the low thermal conductivity of the PCM, which reduces the system's ability to provide hot water at a desired temperature. In addition, the design,

orientation, and position of the heat exchanger significantly affect the phase-changing phenomenon and impact the system's performance. Hence, more research is needed to improve the heat transfer rate during energy storage and recovery, optimize the heat exchanger's design, and find ways to increase the thermal conductivity of the PCM used in the system.

The research direction on this topic has deviated in recent years, where the focus is on optimizing the geometry of individual LHTES units rather than considering the overall performance of the system. This might not be sufficient for developing an effective LHTES system for wide commercialization. There is still a lack of studies on the performance and economic analysis of the whole solar hot water system using LHTES under different operating conditions, weather conditions, and users' demands. Therefore, it may be beneficial to focus on both on-demand performance studies and structure optimisation studies for the faster commercialisation of such a technology.

5. Conclusions and Future Work

Latent heat thermal energy storage (LHTES) has been extensively investigated for domestic water heating purposes over the past years. Three major types of LHTES systems have been developed and studied to improve the energy efficiency of hot water production using solar energy: (i) heat-pipe-assisted LHTES system, (ii) LHTES modules integrated within a water storage tank, and (iii) water storage tank with a separate LHTES tank. Among all, the first and second types of systems have been well examined, with several on-demand system performance studies. However, they still struggled in terms of high cost and complex optimization procedures. Therefore, further research is necessary to optimize the key parameters and bring down the overall cost of the system. The third type of system has not become mature to date. Moreover, the research direction on this topic has deviated in recent years, where the focus is on optimizing the geometry of individual LHTES units rather than considering the overall performance of the system. Further research should work parallelly on both on-demand performance and optimisation studies to speed up the commercialisation of the technology.

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Abbreviations

CFD	computational fluid dynamics
ETHPSC	evacuated tube heat pipe solar collector
HTF	heat transfer fluid
LHTES	latent heat thermal energy storage
MEPCM	microencapsulated phase-change material
NEPCM	nano-enhanced phase-change material
PCM	phase-change material

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