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Seasonal thermal energy storage: A techno-economic literature review

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ABSTRACT

Seasonal thermal energy storage (STES) holds great promise for storing summer heat for winter use. It allows renewable resources to meet the seasonal heat demand without resorting to fossil-based back up. This paper presents a techno-economic literature review of STES. Six STES technologies are reviewed and an overview of the representative projects is provided. The key project parameters and operation performances, including the main heat source fraction, storage efficiency, and energy density, are investigated in the technical review. The economic viability is assessed in terms of the levelized cost of heat (LCOH), storage volume cost, and storage capacity cost. The results show that the tank and pit thermal energy storage exhibits relatively balanced and better performances in both technical and economic characteristics. Borehole and aquifer thermal energy storage exhibits better economic performance, while latent and thermochemical heat storage exhibits better technical performance. Compared to the reference heating alternatives, i.e., natural gas and solar heating for decentralized systems, only pit and low-temperature aquifer thermal energy storage is economically competitive. The LCOH of latent heat storage is the highest. To be economically competitive in the heating market, the LCOH of STES needs to be reduced by half to four times less. Meanwhile, a decision tree for STES selection is introduced to facilitate practical engineering. In compiling the data for this review, we find that STES economic studies are limited in number and often lack transparency in their reporting. Going forward, this should be improved to provide a more solid base for policymaking.

1. Introduction

The built environment accounts for a large proportion of worldwide energy consumption, and consequently, CO_2 emissions. For instance, the building sector accounts for ~40% of the energy consumption and 36%–38% of CO_2 emissions in both Europe and America [1,2]. Space heating and domestic hot water demands in the built environment contribute to ~40% of energy use in the mid- and high-latitude countries, which is expected to rise by 50% by 2050 [3]. Because of the continued increase in the world population and building stock, the heat demand in the built environment is expected to increase in the coming decades [4]. This growth and dominance of fossil fuels in heat supply systems in countries with a cold climate is the main challenge faced in combating climate change and causes a serious issue of local air pollution.

The applications of seasonal thermal energy storage (STES) facilitate the replacement of fossil fuel-based heat supply by alternative heat sources, such as solar thermal energy, geothermal energy, and waste heat generated from industries. In the STES system, the thermal energy primarily generated from sustainable sources is harvested and stored in summer, to be used in winter. It serves as a supplement and adjustment of the heat supply system and shows the potential to coordinate the seasonal mismatch between the heat supply and demand [5], and further improves the overall efficiency of the heating system [6]. Depending on their storage mechanisms, the STES concepts can be classified into three main types: sensible heat storage (SHS), latent heat storage (LHS), and thermochemical heat storage (THS) (Fig. 1).

The development of various STES technologies has been extensively studied from a technical perspective. Xu et al. [7] presented a fundamental review on SHS, LHS, and THS, focusing on storage materials, existing projects, and future outlook. Guelpa and Verda [8] investigated the implementation of STES incorporated with district heating systems and assessed the technical potential of applying STES to various energy systems. The technological status, future development, and market prospect of STES in the UK were reviewed and evaluated in Ref. [9]. The developments and recent trends of large-scale solar district heating plants in Denmark were reviewed in Ref. [10], and the STES projects in Germany were reviewed in Ref. [11].

A few studies have focused on one or two specific STES technologies. Schmidt et al. [12] examined the design concepts and tools,

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Nomenclature

E_t	annual heat production (MWh_{th})
F	fraction
I	investment cost (€)
N	number
n	lifetime
Q	thermal energy (MWh_{th})
r	real discount rate
t	time

Greek symbols

η	efficiency

Abbreviations

ATES	aquifer thermal energy storage
BTES	borehole thermal energy storage
COP	coefficient of performance
COS	cost of storage
GSHP	ground source heat pump
HP	heat pump
LCOE	levelized cost of energy
LCOH	levelized cost of heat
LHS	latent heat storage
PCM	phase-change material
PTES	pit thermal energy storage
O&M	operation and maintenance
ORC	organic rankine cycle
SC	storage capacity
SCC	storage capacity cost
SHS	sensible heat storage
STES	seasonal thermal energy storage
SV	storage volume
SVC	storage volume cost
THS	thermochemical heat storage
TTES	tank thermal energy storage

Subscripts

cyc	cycle
MHS	main heat source
s	storage
sc	storage capacity
th	thermal power

implementation criteria, and specific costs of pit thermal energy storage (PTES) and aquifer thermal energy storage (ATES). Shah et al. [13] investigated the technical element of borehole thermal energy storage (BTES), focusing on ground-heat exchangers, solar collectors, and computer simulation tools. Dahesh et al. [14] evaluated the design, modeling, and construction of tank thermal energy storage (TTES) and PTES, while Bott et al. [15] focused on detailed technical elements including thermal insulation, filling, and waterproofing. The LHS techniques—including phase-change material (PCM) incorporated into a solar collector, storage tank, heat exchanger, as well as PCM slabs and packed bed PCM—were summarized in Refs. [16,17]. The methods of heat-transfer enhancement and design configurations of PCM were evaluated in Ref. [18]. Fleuchaus et al. [19] reviewed the historical and technical development, spatial distribution, and market barriers of ATES. The system configurations, suitable materials, and simulation models of THS-incorporating solar energy in buildings were reviewed in Ref. [20]. The performance of SHS, combined with heat pumps (HPs) in building projects, was examined in Ref. [5] and its energy and exergy performances were evaluated in Ref. [21].

Besides the technical viewpoint, a few studies have also documented a brief review of one or two specific STES technologies from an economic viewpoint. For example, Scapino et al. [22] conducted a comparative study on the cost of storage capacity and energy density of liquid and solid sorption storage systems in the application of low-temperature space heating. Böhm and Lindorfer [23] conducted a techno-economic assessment of THS in a district heating system, considering multiple heat sources, e.g., solar thermal energy, geothermal energy, and industrial waste heat. Huang et al. [24] conducted an economic analysis of TTES, combined with solar thermal energy as heat resource and natural gas boilers as auxiliary heating devices within different technological constraints, e.g., heating terminal units, heating load intensities, and heated areas. They also investigated the feasibility of solar district heating, combined with STES in China, from technical, economic, social, and policy perspectives [25].

Given the above discussion, there is a lack of a comprehensive techno-economic review of STES. A review of the economic competitiveness of STES in the heating market is missing. A better understanding of both technical and economic performances of STES in diverse application contexts can help the decision-making process of selecting and positioning STES in a sustainable heating system. This paper aims to learn the recent developments made in STES by conducting a comprehensive review of both technical and economic parameters and identify the lessons learned from the previous projects to facilitate the future development of STES in a sustainable heat transition. Considering this objective, a summary of the methodology is first provided, followed by the review results of the technical and economic performances of the

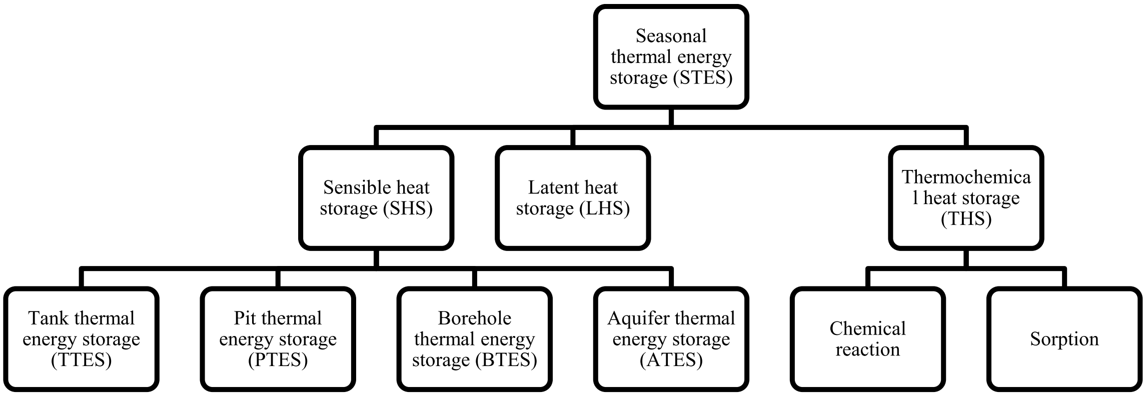


Fig. 1. Summary of current STES technologies.

examined STES projects, lessons learned, and suggestions for future studies.

2. Methodology

To fulfill the research objective, a six-step methodology was proposed and applied in this study (Fig. 2).

2.1. Research scope

This study focuses on the technical and economic performances of STES, including SHS, LHS, and THS. The environmental perspective is beyond the scope of this study, and therefore, not included here.

2.2. Critical literature selection

Over 140 studies were selected during the initial literature collection, using a keyword-based search of article titles, abstracts, and keywords in Scopus and Google Scholar. The keywords included STES, seasonal heat storage, and interseasonal storage. The studies included peer-reviewed journal articles and project reports, written in English. Because of the large collection, a second selection round was performed under the criterion that the selected study should present economic data and a detailed technical assessment. Research papers and project reports that either assessed the economic feasibility of the technologies or provided detailed cost data were prioritized. Several simulation studies were included because of the limited transparency in the reports of the established projects. Finally, the number of studies was narrowed down to 60, with ~10 for each STES technology.

2.3. Literature classification

The collected studies were classified according to STES types (Fig. 1). Table 1 presents an overview of the examined studies, including the year of initial operation, project scale, main heat source, and back-up heating devices. It indicates that the technical review was based on all collected papers, while the economic review was based on 35 studies, because of the availability of economic data. In general, the scale of the STES projects ranged from a house to a community and varied considerably among different STES types. Most of the LHS projects were applied in a greenhouse, while the THS projects were still laboratory prototypes. All projects were located in the mid- and high-latitude countries, and ~80% of them belonged to European countries. The majority used solar thermal energy as the main heat source, followed by waste heat and geothermal energy. In addition, HPs, gas boilers, and electrical heaters were widely used as auxiliary heating devices.

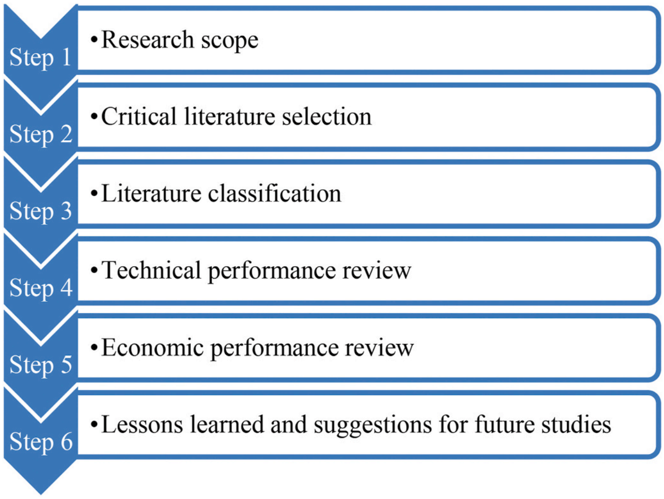


Fig. 2. Schematic of the methodology used in this study.

2.4. Technical performance review

The development status and barriers of different STES types were first summarized to introduce an overview of STES. A representative project of each STES type was presented by showing a schematic layout to introduce an overview and major components of the STES system. The representative projects were selected because they were either the first project implemented in a country or well recognized as a successful case. The key parameters were summed up and calculated to indicate system functions and operation performances. These parameters included annual heat demand, storage volume, storage and heating temperature, heated living area, coefficient of performance (COP) of HP, main heat source fraction (F_{MHS} in Eq. (1)), storage efficiency (η_s in Eq. (2)), and the number of storage cycles per year (N_{cyc} in Eq. (3)). The relations among some key parameters were drawn to help plan a suitable STES system as the technical performances were sensitive to system configuration parameters. Finally, a comparative analysis was conducted between different STES concepts, as well as within the SHS technologies.

$$F_{MHS} = \frac{Q_{MHS}}{Q_{load}} \tag{1}$$

$$\eta_s = \frac{Q_{discharged}}{Q_{charged}} \tag{2}$$

$$N_{cyc} = \frac{Q_{discharged}}{Q_{sc}} \tag{3}$$

where Q_{MHS} is the yearly thermal energy from the main heat source distributed to the total heat demand, Q_{load} is the yearly total heat demand, $Q_{discharged}$ is the yearly thermal energy discharged from the storage, $Q_{charged}$ is the yearly thermal energy charged into the storage, and Q_{sc} is the capacity of the storage medium.

The technical performance review followed the below research steps:

- Introduced the development status, barriers, and one representative project of each STES type.
- Examined key operating parameters of each STES type.
- Identified the characteristics of applications by comparing TTES, PTES, BTES, and ATES.
- Discussed the technical potentials by comparing SHS, LHS, and THS.
- Developed matrices to analyze the trends and relations between different technical parameters.

2.5. Economic performance review

A detailed levelized cost of heat (LCOH) was examined using the techno-economic data available in the examined studies. The levelized cost of energy (LCOE) method is well-applied in the techno-economic analysis, which is a tool for comparing the costs of different electricity generation technologies within their lifetime. Adapting the LCOE formulation for heat production, LCOH can be expressed as

$$LCOH = \frac{I + \sum_{t=1}^{n} \frac{O\&M}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{4}$$

where I is the initial investment, r is the real discount rate, n is the lifetime, $O\&M$ is the annual cost of operation and maintenance, and E_t is the annual heat production.

For the studies whose detailed economic data were unavailable, the storage volume cost (SVC) and storage capacity cost (SCC) were calculated to present the economic feasibility. They are expressed as

$$SVC = \frac{COS}{SV} \tag{5}$$

Table 1
Overview of the examined studies.

Project location	Year of initial operation	Reference	Project scale	Main heat source	Back-up heating devices	Technical review	Economic review
TTES							
Lisse, NL	1995	[26]	One warehouse	Solar thermal	–	+	
Friedrichshafen, DE	1996	[27]	280 apartments	Solar thermal	Gas boiler	+	
Breda, NL	1996	[26]	One factory	Solar thermal	–	+	
Hannover, DE	2000	[28]	One community	Solar thermal	–	+	+
Munich, DE	2007	[29]	300 houses	Solar thermal	HP	+	+
Gaziantep, TR[a]	2010	[30]	One house	Solar thermal	HP	+	
Stockholm, SE[a]	2013	[31]	One house	Solar thermal	HP	+	
Copenhagen, DK[a]	2017	[32]	One house	Solar thermal	Gas boiler	+	+
Marseille, FR[a]	2017	[33]	One house	Solar thermal	Gas boiler	+	+
Marseille, FR[a]	2017	[34]	One house	Solar thermal	Gas boiler	+	+
Jincheon, KR[a]	2017	[35]	One community	Solar thermal	HP	+	+
Marseille, FR[a]	2018	[36]	8 houses	Solar thermal	Boiler	+	+
Panningen, NL	2021	[37]	3920 houses	Solar thermal + waste heat	HP	+	+
PTES							
Stuttgart, DE	1986	[38]	One institute building	Solar thermal + waste heat	HP + co-generation plant	+	
Ottrupgaard, DK	1996	[39,40]	22 houses	Solar thermal	Gas boiler	+	
Steinfurt, DE	1999	[11]	42 apartments	Solar thermal	Electrical heaters	+	+
Chemnitz, DE	2000	[28]	One residential complex	Solar thermal	Gas boiler	+	+
Eggenstein, DE	2008	[41]	One school	Solar thermal	HP + gas boiler	+	+
Osijek, HR[a]	2013	[42]	2000 houses	Biomass trigeneration system	None	+	+
Marstal, DK	2013	[43]	One community	Solar thermal	HP + bio-oil boiler + wood chip boiler with ORC unit	+	+
Dronninglund, DK	2014	[44]	One community	Solar thermal	HP + bio oil boiler + gas engine	+	+
BTES							
Neckarsulm, DE	1997	[45]	One community	Solar thermal	Gas boiler	+	
Anneberg, SE[a]	2002	[46]	90 houses	Solar thermal	Electrical heaters	+	+
Okotoks, CA	2007	[47]	52 houses	Solar thermal	Gas boiler	+	+
Harbin, CN	2008	[48]	One house	Solar thermal	GSHP	+	
Emmaboda. SE	2010	[49]	One factory	Waste heat	External district heating system	+	
Shanghai, CN	2012	[50]	One greenhouse	Solar thermal	None	+	+
Brædstrup, DK	2012	[51]	One community	Solar thermal	HP + gas boiler + electric boiler	+	+
Tianjin, CN	2013	[52]	270 houses	Solar thermal	GSHP	+	+
Torino, IT	2014	[53]	One laboratory	Solar thermal	–	+	
Andalusia, ES[a]	2016	[54]	One community	Solar thermal	Biomass boiler	+	+
Ontario, CA[a]	2017	[55]	One greenhouse	Solar thermal	None	+	+
Aberdeen, GB[a]	2019	[56]	52 houses	Solar thermal	Gas boiler	+	+
Camborne, GB[a]	2019	[56]	52 houses	Solar thermal	Gas boiler	+	+
ATES							
Scarborough, CA	1984	[57]	One community	Waste heat	HP	+	
Berlin, DE	1999	[58]	One community	Waste heat	HP	+	
Brasschaat, BE	2000	[59]	One hospital	None	HP	+	+
Rostock, DE	2000	[60]	108 houses	Solar thermal	HP + gas boiler	+	+
Neubrandenburg, DE	2005	[61]	One community	Waste heat	Boiler	+	
Adana, TR	2005	[62]	One greenhouse	None	None	+	+
Tehran, IR[a]	2013	[63]	One residential complex	Solar thermal	Boiler	+	
Groningen, NL[a]	2020	[64]	11,700 houses	Geothermal	–	+	+
LHS							
Biot, FR	1985	[65]	One greenhouse	Solar thermal	Air heater	+	
Trabzon, TR	1992	[66]	One laboratory	Solar thermal	HP	+	
Reading, GB	1997	[67]	One greenhouse	Solar thermal	None	+	
Çukurova, TR	2003	[68]	One greenhouse	Solar thermal	None	+	+
Elazıg, TR	2005	[69]	One greenhouse	Solar thermal	–	+	+
Lyngby, DK	2015	[70]	One house	Solar thermal	Electrical heater	+	
THS							
Stuttgart, DE	2006	[71]	Laboratory prototype	Solar thermal	–	+	+
Petten, NL	2012	[72]	Laboratory prototype	Solar thermal	None	+	
Perpignan, FR	2014	[73]	Laboratory prototype	Solar thermal	–	+	
Petten, NL	2014	[74]	Laboratory prototype	Solar thermal	–	+	
Wels, AT	2014	[75]	Laboratory prototype	Electrical heater	–	+	
Villeurbanne, FR	2015	[76]	One house	Solar thermal	–	+	
Eindhoven, NL	2017	[77]	One house	Solar thermal	–	+	

(*continued on next page*)

Table 1 (*continued*)

Project location	Year of initial operation	Reference	Project scale	Main heat source	Back-up heating devices	Technical review	Economic review
Loughborough, GB[a]	2018	[78]	Laboratory prototype	Solar thermal	–	+	+
Högskolan Dalarna, SE	2005	[71]	Laboratory prototype	Solar thermal	HP	+	+
Rapperswil, CH	2008	[71]	Laboratory prototype	Solar thermal	HP	+	+
Gleisdorf, AT	2008	[71]	One house	Solar thermal	–	+	+
Dübendorf, CH	2008	[71]	Laboratory prototype	Solar thermal	HP	+	+

[a] Simulation case study.

$$SCC = \frac{COS}{SC} \tag{6}$$

where SV and SC are the storage volume and capacity of the storage, and COS is its cost, considering the storage medium, container or reactor, and charging and discharging device.

The economic performance review followed the below research steps:

- Calculated and compared LCOH within predesigned boundaries.
- Assessed the techno-economic parameters, namely the cost of storage volume and storage capacity for the studies lacking detailed economic data.
- Developed matrices to investigate the relations between economic and technical parameters.

2.6. Lessons learned and suggestions for future studies

The lessons learned from the examined STES studies were identified by summarizing, integrating, and comparing the technical and economic performance review results. A radar plot was drawn to offer a clear understanding of the advantages and drawbacks of each STES type. Furthermore, the LCOHs of different STES types were compared with two heating options for decentralized heating purposes, namely natural gas boilers and solar heating, to present the economic competitiveness of STES in the current heating market. Finally, a decision tree considering different STES types was used to facilitate practical engineering.

3. Technical performance review

3.1. SHS

3.1.1. TTES

TTES is a mature and mass-market technology applied in small commercial and residential buildings, as well as large-scale or district heating systems [9]. Besides STES, TTES is also utilized as short-term storage or a daily thermal buffer. For example, a 30 m^3 hot-water tank was utilized as buffer storage in ATES in Rostock, Germany [60]. One restriction of TTES development is the space constraints, especially for retrofit installations, which usually occurs when fitting very large hot-water tanks into the existing buildings or energy centers without considering TTES integration initially. Besides the space constraints, heat destratification is another barrier that can cause more heat loss in the storage system, especially in very large tanks. Many strategies have been investigated to improve the thermal stratification of TTES [79,80] including 1) inserting baffles in the tank [81–84], 2) a suitable aspect ratio of the tank [85–88], 3) using multiple tanks [89–92], and 4) a suitable design for the shape [85,93–96], position [86,97], and flowrate [85,93–97] of inlet and outlet ports. Also, much attention has been drawn to the efficient insulation of the tank to prevent heat loss during long storage duration [15,98]. Generally, there are two arrangements, i.e., thermal insulation attached to the outer wall of the storage and a double-wall vacuum envelope packed with powder particles [98]. Mass-market insulating materials include inorganic fibrous materials (rock wool and glass wool) and organic foamy materials (expanded polystyrene and extruded polystyrene) [99]. Instead of conventional materials, vacuum insulation panels and aerogels are recognized as the most promising superinsulation materials [100,101].

The first German TTES system connected to a district heating system (Fig. A.1) went into operation in Friedrichshafen in 1996 [27], where a 12,000 m^3 hot-water storage was built with reinforced concrete to store heat for 280 apartments and one kindergarten. The heated living area amounted to ~23,000 m^2, with solar collectors installed in an area of 2700 m^2. Two gas boilers with capacities of 750 and 900 kW$_{th}$ were integrated as back-up heating devices in case of insufficient solar thermal energy available. A solar fraction between 21% and 30% was obtained during 1997–2004. In 2004, another residential zone with ~110 accommodation units was built. Accordingly, solar collectors with an area of 1350 m^2 were mounted. Monitoring results of three years' operation after the extension showed that the solar fraction varied between 24% and 33%, failing to meet the design target (43%). One of the reasons for this was that the annual heat demand was 10% higher than expected. Another reason was that the yearly mean net return temperature was ~20 °C higher than the design value (30 °C), causing a higher storage temperature than expected, and accordingly, an increased heat loss of ~200 MWh$_{th}$ per year.

3.1.2. PTES

PTES is a mature technology for large-scale SHS with high energy density and system efficiency [42]. The efficient insulation to prevent heat loss is also a key issue for PTES. Typical thermal insulation materials—including glass wool, polyurethane, expanded polystyrene, foam glass, and extruded polystyrene—are normally attached inside or outside the construction material [14]. Also, one of the barriers to PTES applications is the degradation related to vapor condensation, which leads to higher heat loss. Liners made of stainless steel, polymers, and elastomers are introduced in the PTES envelope [102]. However, current materials have drawbacks like the potential of corrosion and lower operating temperature. It requires further research on the cover and lining materials. Other challenges include substantial land and excavation requirements. To address this problem, a novel underground thermal energy storage system using a depleted oil well was proposed in Ref. [103].

The first large-scale PTES project was developed at Stuttgart University in 1984 [38]. Fig. A.2 shows a schematic of system. A hole dug in the ground in the shape of a truncated cone was lined with a 2.5-mm-thick high-density polyethylene foil and filled with 4-m-high pebble layer, ~3.75 m of which was flooded with water. The entire storage volume was 1050 m^3. A solar fraction of 62% and a storage efficiency of 82% were achieved in the heating season between 1986 and 1987. Unglazed collectors were used for saving money but could only achieve temperatures below 35 °C, which was not enough for heating purposes. Based on the experiences in Stuttgart, a much larger rectangular version with a storage volume of 8000 m^3 was built in Chemnitz in

1997 and the third generation was built in Steinfurt in 1999 with a geometrical formation of an inverted pyramid frustum having a storage volume of 1600 m^3 [104].

3.1.3. BTES

Recently. a rapid increase in the number of BTES applications has been found in Europe [105] and North America [106]. It is estimated that ~400 BTES projects were in operation in Sweden in 2011 and the number in the Netherlands reached 22,500 in 2007 [107]. However, there are still some barriers limiting BTES development, such as geological conditions. As the installation of BTES systems has higher requirements in terms of hydraulic conductivity and natural groundwater flow, geothermal probes are always required to be installed before borehole drilling [9]. Another barrier is that there is a start-up process (3–4 years) in the system operation—which means that the storage efficiency is very low in the first year of operation and improves over time, because heating the ground materials surrounding the boreholes takes time. From a long-term perspective, BTES can cause a gradual increase in average ground temperature, groundwater movement, and soil water content loss [108–110]. Besides, in order to reduce the thermal interferences between the boreholes, some solutions have been reported including using a thermal baffle [111], pipe insulation installed on the upward branch pipe [112], and a suitable geometric dimension of the borehole considering spacing, diameter, and depth [113–115].

The Drake Landing Solar Community in Okotoks, Canada, developed the first BTES system, as shown in Fig. A.3, which meets over 90% of residential space-heating needs through solar thermal energy [47]. It uses two water-based buffer storage tanks, 34,000 m^3 of borehole storage, and 2293 m^2 of solar collectors to supply the space heating and hot-water needs of 52 houses with a total heated living area of 7540 m^2. With a 10-year reliable operation, the solar fraction was calculated as an average of 96% for 2012–2016 and even reached 100% in the 2015–2016 heating season.

3.1.4. ATES

At the end of 2017, 3000 ATES projects were estimated to be in operation in Europe [12]. The successful projects were concentrated in only a few mid- and high-latitude countries: 2500 in the Netherlands, 220 in Sweden, 55 in Denmark, and 30 in Belgium [19]. Before 2000, most ATES systems provided heating and cooling to individual buildings, such as hospitals and offices. The application has recently started turning to district heating systems [116]. An ATES project requires suitable hydrogeological conditions, as they have a strong influence on the system's performance, as well as relatively high thermal loads; moreover, it must meet the regulatory requirements. For example, the Dutch policy currently has two restrictions on ATES: (1) the temperature of the injected water is not allowed to be above 25–30 °C and (2) thermal imbalance is not allowed between the hot and cold wells [117]. Because of the restriction of the aquifer temperature, 99% of ATES systems worldwide are operating at low temperature (<25 °C) [19].

The first German ATES central solar heating system went into operation in Rostock in 2000 [60] (Fig. A.4), supplying district heating and domestic hot water to 108 apartments with a total heated living area of 7000 m^2. The buildings mounted 980 m^2 solar collectors on the roof, and below the buildings, a doublet of wells was drilled 30 m underground. The target was designed to meet half of the total heat demand every year, which was reached after three years' operation with a solar fraction of 49%.

3.1.5. SHS comparison

Detailed technical data of the examined studies are listed in the Appendix (Table A.1). The widely applied technical parameters, including annual heat demand, storage volume, storage and heating temperature, heated living area, COP of HP and system, main heat source fraction, storage efficiency, and the number of storage cycles per year, were investigated to evaluate the performance of TTES, PTES, BTES, and ATES. Most of the examined projects published the specific number of heated living areas, storage and heating temperature, annual heat demand, solar collector area (projects using solar thermal energy as the main heat source), storage volume, and main heat source fraction, or yielded the possibility to calculate these parameters. However, more data, such as storage capacity, COP of HP and system, HP capacity, storage efficiency, and the number of storage cycles per year, should be revealed as well. Besides, it was found that projects in Germany and Denmark provided better data accessibility.

The geographic requirements, advantages, and limitations of SHS technologies learned from the reviewed studies are listed in Table 2. Some technical parameters of these projects are further discussed in the following figures. TTES and PTES have relatively high energy density and thermal conductivity. They can be built at nearly any location, owing to their fewer requirements of geographic conditions. Little impact on the natural geology is reported while efforts are needed to prevent leakage. BTES and ATES can be used for both heating and cooling purposes and face fewer leakage problems. However, their energy density and thermal conductivity are relatively low, as ground materials are directly used as the storage medium. Because BTES and ATES require special geological conditions, such as no or low natural groundwater flow, a long initial process is required for an extensive geological investigation. Besides, with a direct touch with natural geology, the storage temperature of BTES and ATES is relatively limited and a long start-up process (3–4 years) is required to achieve the typical performance.

The technical performance of STES systems is sensitive to their configuration parameters. For example, the solar collector area impacts the main heat source fraction, while the storage volume influences the level of storage efficiency. Therefore, several key parameters are investigated to facilitate a better understanding of how they relate to each other and the extent to which they influence the technical performances.

The variation in the maximum storage temperature with storage volume in water equivalent is shown in Fig. 3. It indicates that the storage temperatures of BTES and ATES are limited to 70 °C as ground materials are used as the storage medium without good insulation. The majority storage volume in water equivalent of SHS ranges from 100 to 50,000 m^3. ATES has the advantage of providing the largest storage volume, because it uses a natural aquifer as the storage medium.

The relation between the storage efficiency and storage volume in water equivalent is presented in Fig. 4. Note that the storage efficiencies of BTES and ATES are limited to 65%, because ground materials are used as the storage medium. TTES and PTES, in general, have higher storage

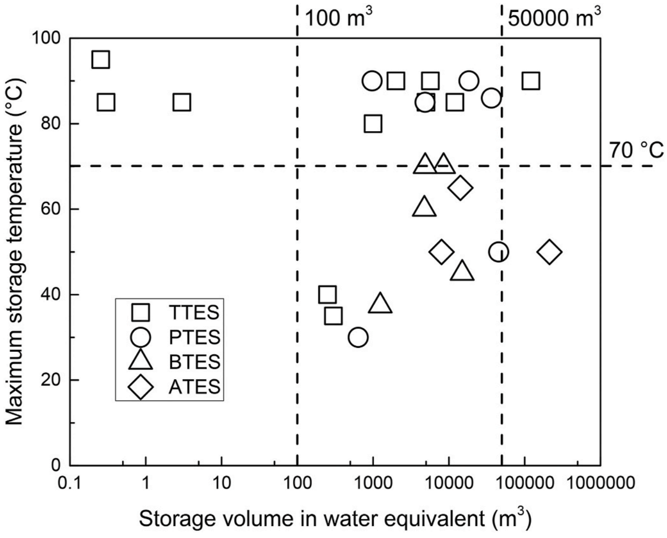


Fig. 3. Storage temperature and volume in water equivalent.

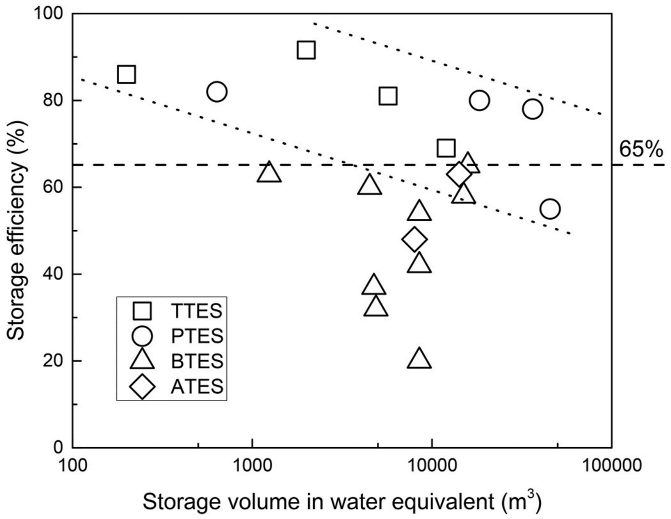


Fig. 4. Storage efficiency and volume in water equivalent.

efficiencies than BTES and ATES because of their good insulation. Within TTES and PTES, the storage efficiency decreases with an increase in storage volume in water equivalent, which can be explained by more heat loss caused by a higher level of heat destratification.

Fig. 5 shows the main heat source fraction with the ratio of the solar collector area to annual heat demand in the projects, with solar thermal energy as the main heat source. A higher ratio of the solar collector area to the annual heat demand means that most of the annual heat demand is met by solar thermal energy. In case of BTES and ATES, a higher ratio results in a higher main heat source fraction. In terms of TTES and PTES, the ratio mainly ranges between 1 and 2 because the storage temperature is normally close to 100 °C. Thus, increasing the solar collector area does not lead to more stored thermal energy.

HPs are widely used as auxiliary heating devices in STES systems. In the projects with solar thermal energy as the main heat source, the ratio of storage volume in water equivalent to the solar collector area indicates the relation between heat demand and heat supply. A higher ratio means a larger heat demand but lesser heat supply from the main heat source. Therefore, the mismatch between the heat supply and demand needs to be compensated by HPs. Fig. 6 presents the relation between the COP of HP and the ratio of the storage volume in water equivalent to the solar collector area. The COP of HP increases with this ratio, and shows that HP, as a supplementary device, performs better with the requirement of compensating more thermal energy.

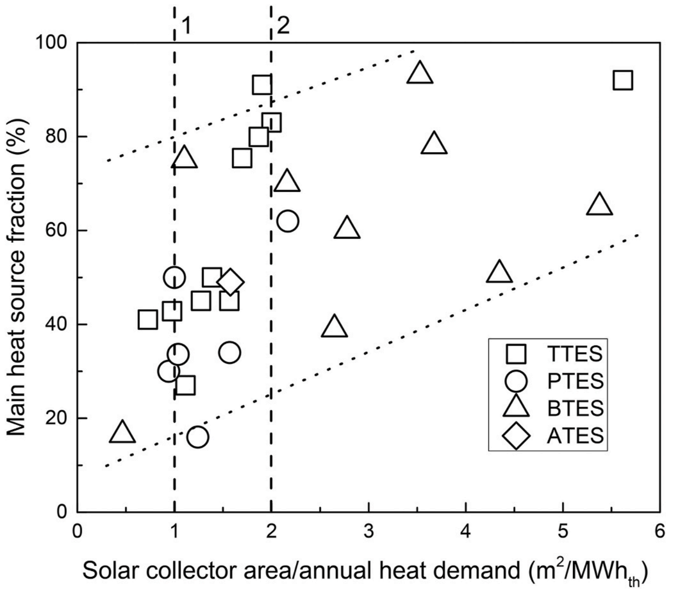


Fig. 5. Main heat source fraction and solar collector area over annual heat demand.

3.2. LHS

LHS is recognized as a suitable concept of STES due to the high energy density and the fact of being able to maintain a relatively constant temperature during the phase-change process. A summary of the studies conducted on LHS is summarized in the Appendix (Table A.2). The implementation of PCMs into building envelopes, e.g., wallboard [120], walls [121], shutters [122], floors [123], and ceilings [124], has been extensively studied for passive heating and cooling purposes. However,

Table 2
Technical comparison of SHS technologies [5,9,118,119].

Storage technology	TTES	PTES	BTES	ATES
Storage medium	Water	Water and gravel	Ground material (soil/rock)	Ground material (sand/gravel … -water)
Geological requirements	• Stable ground conditions • Preferably no groundwater • 5–15 m deep	• Stable ground conditions • Preferably no groundwater • 5–15 m deep	• Drillable ground • Groundwater favorable • High heat capacity • High thermal conductivity • Low hydraulic conductivity • Low natural groundwater flow • 30–100 m deep	• Natural aquifer layer with high hydraulic conductivity • Confining layers on top and bottom • Low natural groundwater flow • Suitable water chemistry at high temperatures • Aquifer thickness 20–50 m deep
Advantages	• No special geological condition needed • Most mature technology • High stratification • High heat capacity • Easy to install	• No special geological condition needed • Leaving natural aquifer untouched	• Can be used for both heating and cooling • Needs less surface area in case of a vertical borehole • Needs less excavation in case of horizontal duct • Less sensitive to outdoor climate • Feasible for very large and very small applications	• Can be used for both heating and cooling • Ability to produce direct cooling without supporting device • Less maintenance needed • More efficient heat transfer than BTES
Limitations	• High heat loss • Potential corrosion • Potential leakage	• Lower stratification than TTES • Potential leakage • Lower energy density than TTES	• Special geological condition needed • High heat loss • Low energy density • Long initial process for geological investigation • Start-up process needed	• Special geological condition needed • High heat loss • Low energy density • Clogging effects • Long initial process for geological investigation

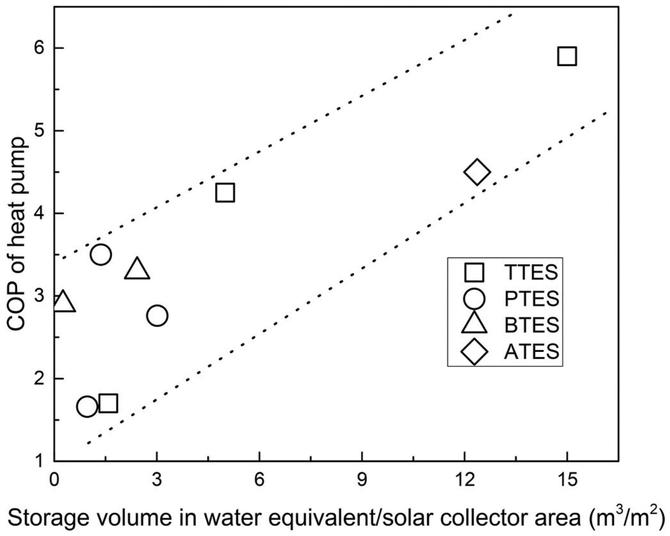


Fig. 6. COP of HP and storage volume in water equivalent over solar collector area.

the storage ability of most of these applications is relatively low and their heating and cooling performances are uncontrollable, and therefore, they are only suitable for short-term storage. Active LHS, where a main heat source is implemented, plays a significant role in seasonal storage. Since the 1970s, LHS has been applied in greenhouses. The design of LHS systems for greenhouses is dependent on the desired control range of temperature inside the greenhouses and local climate and resources. Some successful implementations have been reported in Turkey [68,69], Tunisia [125], France [65], UK [67], and China [126]. However, the biggest challenge of implementing LHS as seasonal storage is a lack of fully commercial PCM products, and the potential corrosion, flammability, and toxicity of PCMs significantly reduce their usage.

An LHS system in Çukurova, Turkey, using 6000 kg paraffin wax in a 12 m^3 steel tank as PCM was presented in Ref. [68]. With a 27 m^2 solar collector area, it has a melting latent heat of 190 kJ/kg and a melting temperature of 48–60 °C, providing heat to a 180 m^2 greenhouse (Fig. A.5). During the charging period, the system achieves an average energy efficiency of 74.3% and exergy efficiency of 65.2%.

3.3. THS

THS has drawn increasing attention because of its high energy density and negligible heat loss, as the sorbate and substance are placed separately. The examined studies on THS are categorized into two system configurations (open and closed systems). Detailed data regarding this can be found in the Appendix (Table A.3). The open system is a simple system operating at atmospheric pressure, while the closed system has more complex operation conditions with a higher discharging temperature and pressure. Currently, THS is still far away from complete market commercialization, and thus, further research on materials and system configuration is required.

Long-term open sorption storage (Fig. A.6) for solar thermal space heating with novel zeolite honeycomb structures, instead of ordinarily employed fills, was built in a house at Stuttgart University, Germany, in 2006 [71]. This storage was integrated with a 1 m^3 combi-storage, evacuated tube collectors with an area of 20 m^2, and a 7.85 m^3 sorption storage. Humid outlet air was used as the sorbate, and an auxiliary heater was applied in case the sorption system failed to meet the heat demand. The energy density of the prototype storage was 120 kWh$_{th}$/m^3 and the discharging rate ranged between 1 and 1.5 kW$_{th}$. Compared to ordinarily fills, the newly designed zeolite structures achieved better adsorption properties and a lower pressure loss.

3.4. Comparison

To provide comprehensive results for the technical performance review, three main STES concepts, namely SHS, LHS, and THS, were compared to indicate the level of maturity, advantages, and limitations (Table 3). SHS is the most stable and mature concept but some technologies have high requirements for geological conditions. The energy density of SHS is relatively lower than those of LHS and THS, and therefore, SHS normally requires a large storage volume. LHS with a high energy density can provide heat at an almost constant temperature. However, its storage materials are usually corrosive, poisonous, and lack thermal stability. THS has the highest energy density and negligible heat loss as the storage medium is normally stored separately; however, it requires a more complicated system, and the instability problems of the storage materials need to be addressed.

The project scale and initial operation year of the examined projects are presented in Fig. 7. Most examined LHS projects started before 2005, and few projects were reported after that. The examined THS projects were initially started after 2005, but they have a very small scale as the technology is still in the stage of laboratory research. Compared to LHS and THS, the project scales of SHS are much larger, from one house to one community, indicating the maturity of these technologies in commercialization. Note that several BTESs were installed in the 2000s, with the project scale ranging between 1 and 1000 household equivalents.

4. Economic performance review

4.1. LCOH

Different LCOH values can be calculated according to the system boundaries. As shown in Fig. 8, four LCOH values were calculated considering 1) only the renewable energy input part, 2) only the thermal storage part, 3) only the back-up heating device part, and 4) the overall STES system.

The costs of the examined STES projects were converted to 2019 constant prices in euro using the inflation and exchange rate derived from the Organization for Economic Co-operation and Development [127,128]. In terms of certain missing economic data in several projects, the O&M cost is assumed based on the ratio of that and the investment in projects with available data. The O&M cost of the renewable energy input and thermal storage is assumed as 1% of their initial investments, and that of the overall STES system is assumed as 3.5% of the overall

Table 3
Technical comparison of different STES concepts [9,22].

Storage concept	SHS	LTS	THS
Maturity level*	3	2–3	1
Advantages	• Unhazardous and low-cost material • Relatively simple system • Reliable • Easy to control	• High energy density • Provide heat at almost constant temperatures	• High energy density • Compact system • Negligible heat loss • Potentially non-toxic materials
Limitations	• Low energy density • Large volume required • Heat loss • Geological requirements	• Lack of thermal stability • Potential degradation • Potential corrosion	• Material instability • Cyclability problems • Complex system

(note: maturity levels: 1 = research and development; 2 = demonstration and deployment; 3 = commercialization.).

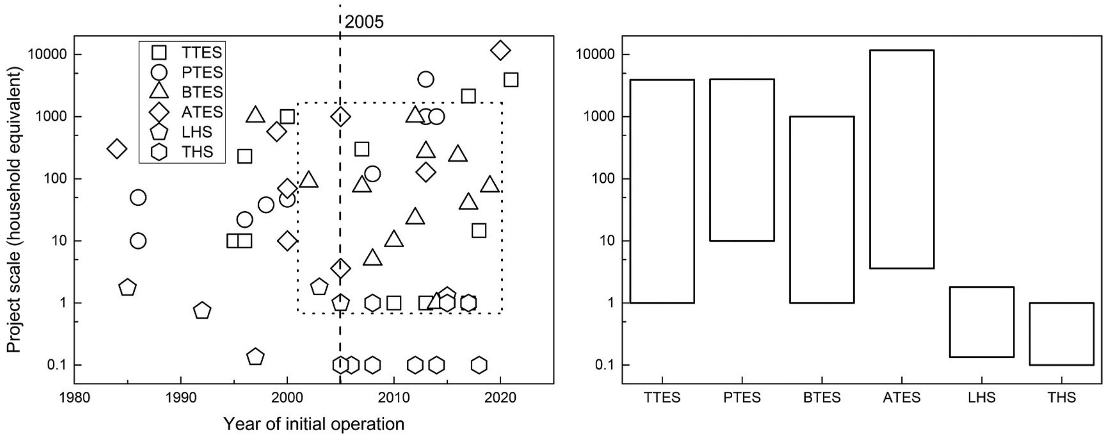
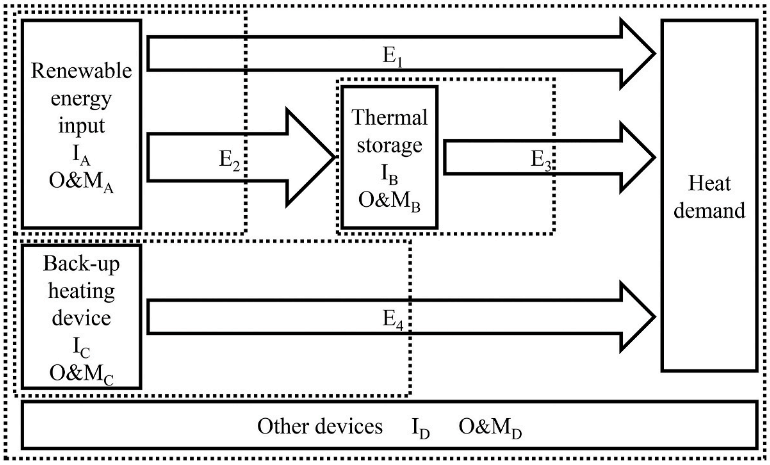


Fig. 7. Project scale and year of initial operation (the left figure shows the scale and initial operation year of individual projects; the right figure provides the range of application scale of each technology).



LCOH of renewable energy input:

$$\frac{I_A + \sum_{t=1}^{n} \frac{O\&M_A}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_1+E_2}{(1+r)^t}}$$

LCOH of thermal storage:

$$\frac{I_B + \sum_{t=1}^{n} \frac{O\&M_B}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_3}{(1+r)^t}}$$

LCOH of back-up heating device:

$$\frac{I_C + \sum_{t=1}^{n} \frac{O\&M_C}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_4}{(1+r)^t}}$$

LCOH of overall STES system:

$$\frac{I_A + I_B + I_C + I_D + \sum_{t=1}^{n} \frac{O\&M_A + O\&M_B + O\&M_C + O\&M_D}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_1+E_3+E_4}{(1+r)^t}}$$

Fig. 8. Specific system boundaries for LCOH analysis.

system investment when the data are not available. The real discount rate is considered as a constant (5%) [129,130].

The LCOH calculation results of the renewable energy input, thermal storage, back-up heating device, and overall STES system of the examined projects are listed in Table 4, based on the data provided in the Appendix (Table A.4). The LCOH of the thermal storage and overall system varies considerably with different projects among each SHS type. The average LCOH of the thermal storage of BTES is higher than the other storage types because of the high excavation fee. Only one study has recorded the LCOH of the overall system for both LHS and THS. As expected, the LCOH of the overall system of LHS is higher than that of most of the SHS projects; however, THS has a relatively lower LCOH of the overall system, indicating better cost-effectiveness than LHS. Note that these results are based on the limited available studies and the LCOH of the overall system of THS is calculated from an ideal simulation case study. This may cause uncertainty in LCOH calculation.

Fig. 9 presents the LCOH of the overall STES system and the share of heat discharged from the storage in the annual heat demand. A general trend can be observed, where a higher share results in a higher LCOH of the overall system, indicating less attraction from an economic perspective. This is because there is always heat loss in the storage device. A higher share of heat discharged from the storage implies a higher heat loss in the overall system, causing a lower LCOH of the overall system.

Fig. 10 presents the LCOH of the thermal storage and storage efficiency. BTES projects have much higher LCOH of the thermal storage (over 160 €/MWh$_{th}$) and lower storage efficiency (up to 60%) than other STES types. A general trend is that a higher storage efficiency, meaning more heat recovered from storage, leads to a lower LCOH of the thermal storage.

4.2. SVC and SCC

Table 4 lists the cost of storage volume and storage capacity in the examined studies. For SHS, the storage cost includes the costs of storage materials and relevant storage devices, such as the container and charging and discharging devices. In contrast, for some of the LHS and THS projects, the storage cost only refers to the storage material cost, as most of the projects are at the level of laboratory prototype. Apparently, the costs of storage volume and storage capacity of LHS and THS are hundreds of times higher than those of SHS. This can be partly explained by the stage of technology development and project scale. The SVC and SCC of TTES and PTES are higher than those of BTES and ATES. Besides, the studies conducted in Copenhagen, Denmark [32], and Marseille,

Table 4
Economic performance review of the examined projects (2019 €).

Project	Reference	LCOH (€/MWh$_{th}$)				SVC (€/m^3)	SCC (€/kWh$_{th}$)
		Renewable energy input	Thermal storage	Back-up heating device	Overall system		
TTES							
Hannover, DE	[28]	–	–	–	–	322.87	5.55
Munich, DE	[29,131]	–	–	–	–	179.54	2.13
Copenhagen, DK	[32]	60.74	–	–	241.75	5439.40	–
Marseille, FR	[33]	107.68	–	–	212.12	3121.24	–
Marseille, FR	[34]	71.5	–	–	156.5	4855.26	–
Jincheon, KR	[35]	67.19	87.01	413.87	257.95	140.19	–
Marseille, FR	[36]	135.16	142.28	995.28	243.56	108.13	–
Panningen, NL	[37]	–	–	–	130.01	160.2	0.69
PTES							
Steinfurt, DE	[104]	–	–	–	–	456.78	–
Chemnitz, DE	[11,28]	–	–	–	–	105.05	2.71
Eggenstein, DE	[28]	–	–	–	–	113.02	2.91
Osijek, HR	[42]	46.9	78.75	–	54.77	58.14	–
Marstal, DK	[43,132]	59.57	55.73	60.92	87.69	36.60	0.46
Dronninglund, DK	[44]	36.26	20.71	28.16	46.74	39.64	0.47
BTES							
Anneberg, SE	[46]	29.91	20.61	84.69	105.77	2.76	–
Okotoks, CA	[47,133]	80.92	128.79	–	410.72	15.95	–
Shanghai, CN	[50]	–	–	–	211.87	–	–
Brædstrup, DK	[51,132]	54.18	177.44	95.46	81.19	16.91	0.8
Tianjin, CN	[52]	–	–	–	110.84	–	–
Andalusia, ES	[54]	34.36	51.61	163.3	130.8	8.6	0.41
Ontario, CA	[55]	63.05	203	–	118.18	16.45	–
Aberdeen, GB	[56]	96.59	286.28	126.53	307.05	14.45	–
Camborne, GB	[56]	78.44	358.49	195.47	434.35	14.45	–
ATES							
Brasschaat, BE	[59]	–	44.88	37.76	86.22	–	–
Rostock, DE	[60]	99.82	155.28	145.13	263.77	12.34	–
Adana, TR	[62]	–	–	–	50.72	–	–
Groningen, NL	[64]	–	13.78	–	–	–	0.054
LHS							
Çukurova, TR	[68,134]	–	–	–	382.69	–	–
Elazıg, TR	[69]	–	–	–	–	1383.60	148.12
THS							
Stuttgart, DE	[71]	–	–	–	–	3661.85	164.78
Loughborough, GB	[78]	–	–	–	193.18	1233.3	1.49
Högskolan Dalarna, SE	[71]	–	–	–	–	4310.32	78.82
Rapperswil, CH	[71]	–	–	–	–	2554.6	3065.52
Gleisdorf, AT	[71]	–	–	–	–	5362.69	701.28
Dübendorf, CH	[71]	–	–	–	–	255.46	37.31

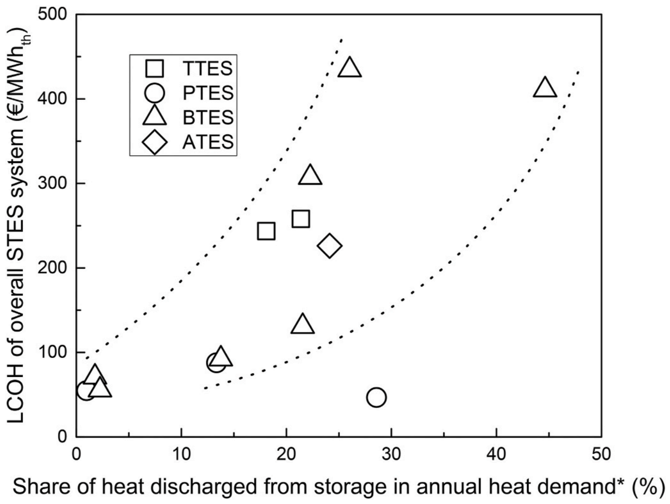


Fig. 9. LCOH of an STES system and the share of heat discharged from storage in annual heat demand. (Note: the share of heat discharged from storage in annual heat demand is expressed as $E_3/(E_1+E_3+E_4)$ from Fig. 8).

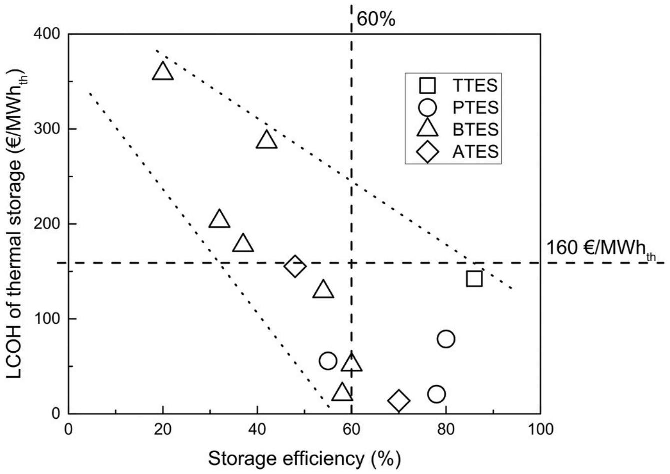


Fig. 10. LCOH of thermal storage and storage efficiency.

France [33,34], have indicated that when a TTES is built in a small-scale project, the SVC can be very high.

Fig. 11 shows the relation between the investment cost of thermal storage over storage volume in water equivalent and that in water equivalent with the data obtained from the projects examined in this

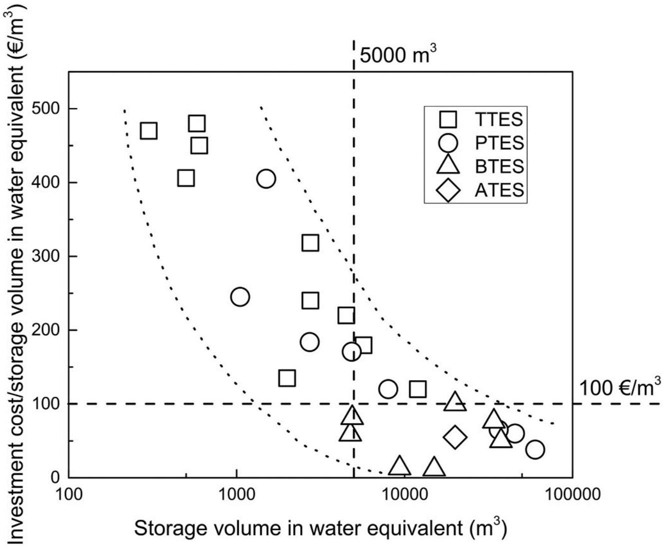


Fig. 11. Investment cost over storage volume in water equivalent and storage volume in water equivalent.

study as well as those derived from Refs. [11,38]. It indicates the impact of project scale on the specific investment cost. A clear trend is observed here, where the storage volume in water equivalent is associated with the project scale. The ratio of the investment cost and storage volume in water equivalent decreases with an increase in the storage volume in water equivalent. Besides, BTES and ATES are often applied in large projects with the storage volume in water equivalent over 5000 m^3, and the specific investments are very low (up to 100 €/m^3). TTES is often applied in projects with a few houses, owing to the space constraints and small-scale TTES projects incur very high investment costs.

5. Lessons learned and suggestions for future studies

5.1. Techno-economic analysis

To offer a clear understanding of the advantages and drawbacks of each STES type, an integrated matrix with six characteristics is drawn in Fig. 12 to show the overall performances of the STES types. Within the assessment of each characteristic, a higher score refers to better performance. For example, a higher score in energy density and geological requirements refers to higher energy density and fewer requirements under geological conditions, respectively. TTES and PTES are found to exhibit relatively balanced performance in the examined characteristics and cover larger areas in the matrix. The economic performances of BTES and ATES are better than their technical performances, while the opposite feature is observed for LHS and THS. This indicates that LHS and THS are a promising alternative when the cost is reduced using better storage materials or more mature technology.

5.2. Economic competitiveness

The economic competitiveness of STES types is compared with that of the existing heat supply alternatives, selecting the applications of natural gas boilers and solar heating in decentralized heating as reference. The LCOH of the reference is calculated based on the techno-economic data derived from Refs. [135–140]. The investment costs of the heat supply technologies are converted to constant 2019 prices. During the calculation of the natural gas boiler, the European average price of natural gas in 2019 is applied, which is 17.47 €/GJ for residential purposes [136]. In terms of solar heating, the specific cost of solar collectors is in accordance with the average number of examined projects in this study (380 €/m^2).

The results of the LCOH comparison are presented in Fig. 13 (left). A large range of LCOH exists in some STES as varied economic input data are observed in the reviewed studies. The potential reasons of a very high LCOH include a) an oversized project scale, which means low heat demand but high heat supply; b) overpriced solar collectors; c) excessive main heat source fraction, which means very low heat production from the back-up heating devices; and d) unsuitable geological conditions. The factors causing a very low LCOH include a) no main heat source (in the case of ATES), b) no back-up heating devices, c) low-priced solar collectors, d) low-priced borehole, and e) a low share of heat discharged from the storage in annual heat demand.

Based on the abovementioned reasons, the LCOH of STES is normalized and the results are presented in Fig. 13 (right). Table A.5 provides detailed explanations and data for the normalization. As shown in Fig. 13 (right), only the PTES projects and a part of the ATES projects are economically competitive with the reference systems. The PTES projects selected for the LCOH calculation serve as part of district heating, indicating better economic performance compared to decentralized heating. In terms of ATES, some projects without a main heat source or back-up heating device have very low LCOH, e.g., supplying low-temperature heat (25 °C) to a greenhouse in Adana, Turkey [62]. This indicates that ATES can be economically much competitive when

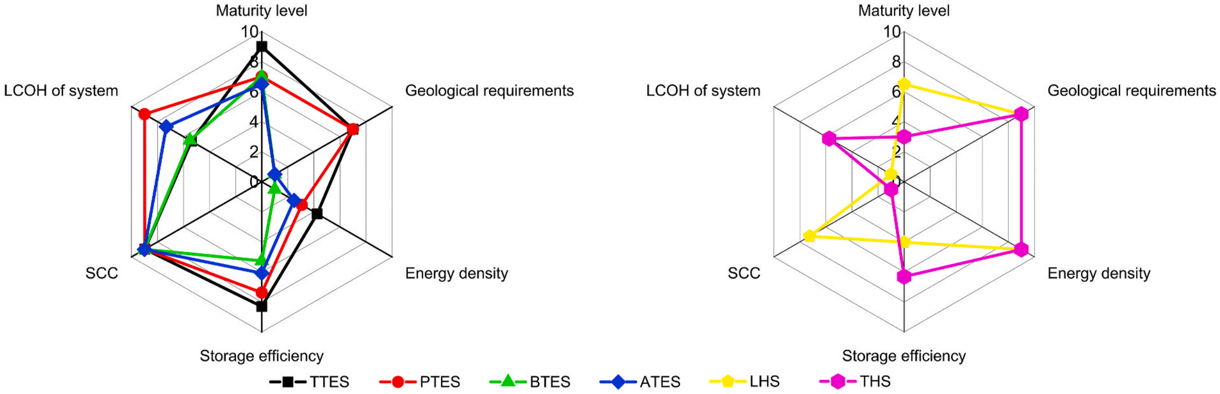


Fig. 12. Comparison of six STES types with different characteristics (the left figure shows the results of SHS and the right figure shows those of LHS and THS).

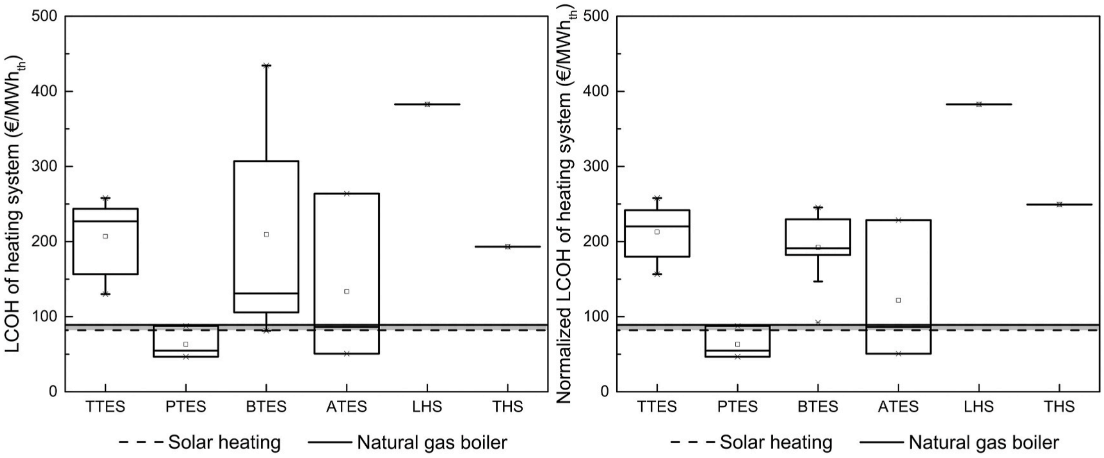


Fig. 13. LCOH of STES systems in comparison with other heating options (the left figure shows the original results and the right figure shows the normalized results).

used for low-temperature heating purposes. The LCOH of TTES and BTES is over twice that of the reference systems. The LCOH of LHS is the highest (over four times higher than the reference systems). To be made economically attractive, the LCOH of LHS and THS needs to be reduced by 60%–80%. Thus, measures are required to further reduce the STES costs to promote its economic feasibility in the heating market, for example, implementing large-scale STES in existing and new district heating systems, material improvements, and better drilling and insulation methods. The data for calculating LCOH are derived from the limited-access economic studies of STES. Future projects should be more transparent to provide a solid base for policymaking.

5.3. STES selection

Selecting a feasible STES technology depends on various features and parameters, including geological and hydrological conditions, project scale, required cooling demand, and costs. To facilitate practical engineering, a decision tree that may guide potential STES selection is introduced, as shown in Fig. 14.

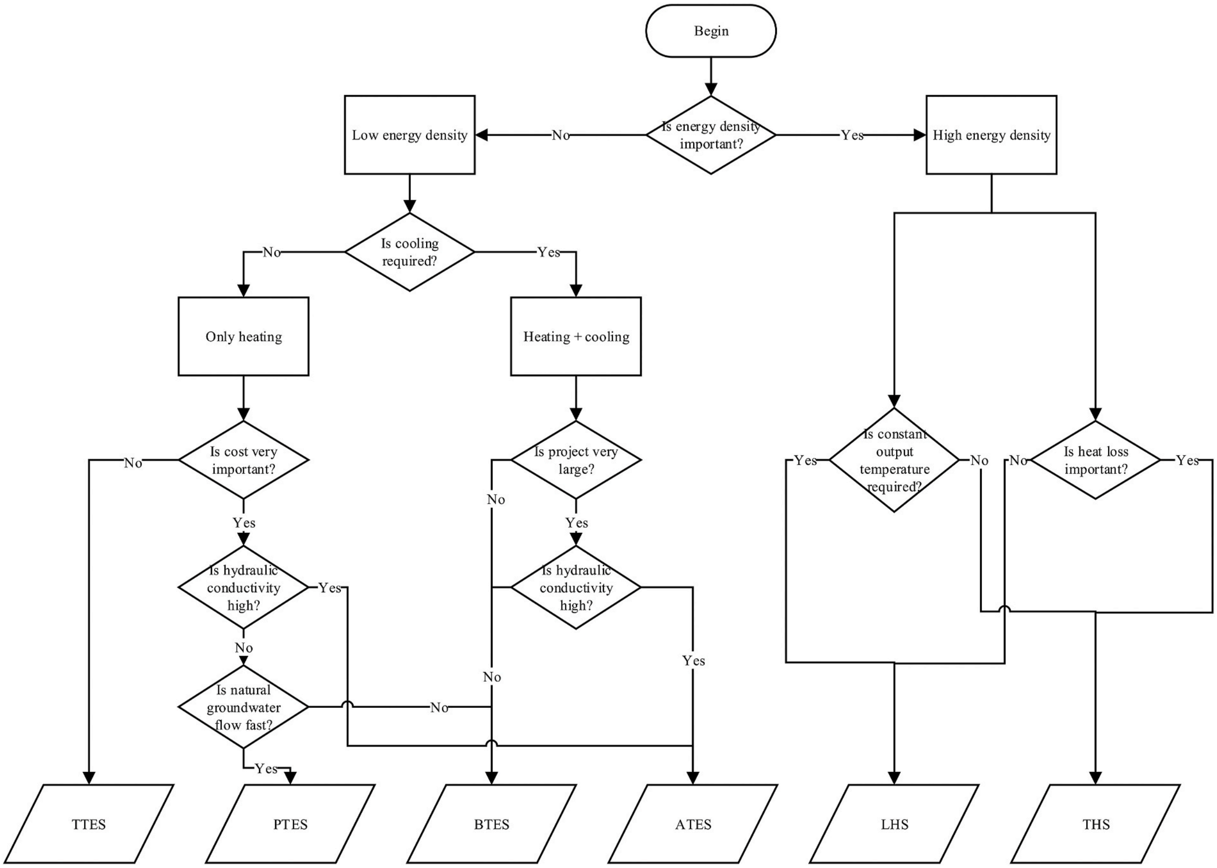


Fig. 14. Decision tree for selecting STES types.

6. Discussion

A limit of this study is the inclusion of the representative projects. The objective of this study is to learn the recent developments made in STES by conducting a comprehensive literature review of both technical and economic indicators. It requires detailed technical parameters and economic data to analyze the trends and relations between different technical parameters and to calculate the LCOH. Some representative projects were not included because they were either not reported in English which is difficult for readers to track or lacking in transparency in techno-economic parameters. The review results are based on the selected and examined studies. For example, this work discussed the storage efficiency of BTES and ATES based on the examined studies. However, the storage efficiency increases as the size of the BTES and ATES systems increases [141–143]. The inclusion of projects with a larger scale will increase the results of storage efficiency. More transparency is required for future studies to provide a solid base for techno-economic analysis.

Both established projects and simulation studies were included in this study. The latter was included because of their transparent reporting in techno-economic parameters. However, the inclusion of two types of studies brings uncertainty to the comparison of the technical performance. For example, a few key technical indicators (e.g., main heat source fraction and storage efficiency) were reviewed and compared to assess the technical performance of STES. The value of these indicators was either extracted from the selected studies or calculated in this study. The same equations were used to calculate those indicators. In terms of the established projects, the key technical indicators were mainly obtained from the project measurements. For the simulation studies, the technical indicators were obtained from the numerical simulation which often includes some simplifications. The established projects and simulation studies were distinguished in Table 1. The simulation studies often used TRNSYS, MINSUN, or mathematical models in Matlab. These tools are widely used in STES modeling and proved to have a good level of accuracy [5,13,144]. The impact of the simplifications on the indicator comparisons was not considered in this study.

In order to pursue a good technical performance like a high main heat source fraction and storage efficiency, STES systems are often oversized, which results in a negative impact on economic performance. For example, Drake Landing Solar Community achieved an average of 96% in the main heat source fraction, but its LCOH was calculated to be 410.72 €/MWh$_{th}$. Both numbers are much higher than the average level of BTES systems. It is suggested to investigate how to balance the technical and economic performances in future works. Also, solar thermal energy plays a dominant role as the heat supply in current STES systems. Diverse heat supply options (e.g., waste heat, geothermal energy, and power-to-heat) can be implemented in STES systems based on local conditions.

7. Conclusions

STES is a key technology for replacing fossil-based heat supply with renewable heat sources, such as solar thermal energy, geothermal energy, or waste heat generated from industries. This paper presents a comprehensive techno-economic literature review of STES technologies and projects. Within the class of SHS technologies, TTES and PTES are mature and mass-market technologies and have an advantage in terms of storage temperature and efficiency because of their good insulation; however, their space requirement and potential of leakage are substantial, and thus, limits their application. Also, their storage efficiency was found to decrease with an increase in storage volume in water equivalent. BTES has developed rapidly in recent years, but it can only be built in locations with suitable underground conditions, and efforts are required to shorten the start-up process. ATES has been increasingly adopted in district heating systems but under the condition of subsurface aquifer availability within a suitable depth. BTES and ATES can be used for both heating and cooling purposes and provide a large storage volume, but their energy density and thermal conductivity are relatively low. LHS with a high energy density can provide heat at an almost constant temperature; however, its current storage materials are usually corrosive, poisonous, and lack thermal stability. THS has the highest energy density and low heat loss as the storage medium is normally stored separately, but it requires a more complicated system, and the instability problems of the storage materials need to be addressed. HPs are widely used as auxiliary heating devices in STES systems, and a higher COP can be obtained by a higher ratio of the storage volume in water equivalent to the solar collector area. Also, solar thermal energy plays a dominant role as the heat supply in current STES systems. The implementation of diverse heat supply options should be investigated in future studies. In general, LHS and THS are advantageous in terms of technical performance, such as high energy density and few geological requirements while SHS is more mature and largely applied in the current heating market.

The economic study indicates that the configuration parameters and technical performance substantially impact the economic performance, for example, the storage volume and efficiency have a positive impact, while the share of heat discharged from the storage has a negative impact. The average LCOH of the thermal storage of BTES is higher than that of other storage types, while the cost of storage volume and storage capacity of LHS and THS are hundreds of times higher than those of SHS. Compared to the reference heating options, i.e., natural gas boilers and solar heating for decentralized heating systems, none of the STES types is economically competitive, except for PTES and low-temperature ATES. Their LCOH is calculated to be lower than those of the reference systems. The LCOH of LHS is the highest (over four times higher than the reference systems). Thus, to be economically competitive in the heating market, the LCOH of STES must be generally reduced by half to four times less. Continuous efforts are required to explore and improve the technology as well as reduce the costs. In addition, the current economic study in the public domain is limited, and therefore, future projects should be more transparent to provide a solid base for policymaking.

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.

Acknowledgments

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Appendix

See Fig. A.1-A.6 and Tables A.1–A.5.

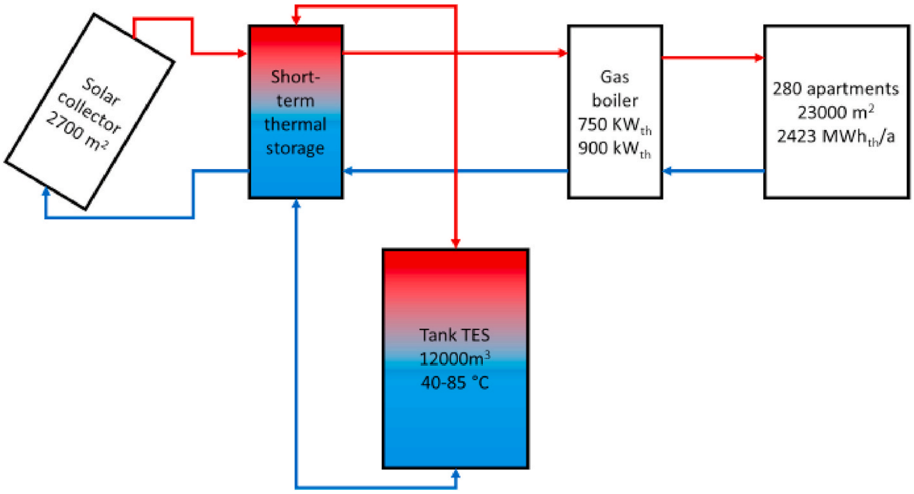

Fig. A.1. Schematic of TTES in Friedrichshafen, Germany (adapted from Ref. [145]).

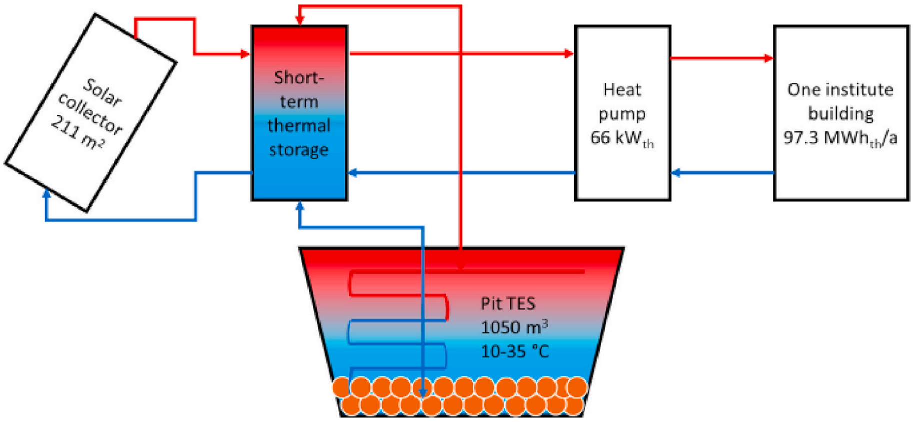

Fig. A.2. Schematic of PTES in Stuttgart, Germany (adapted from Ref. [38]).

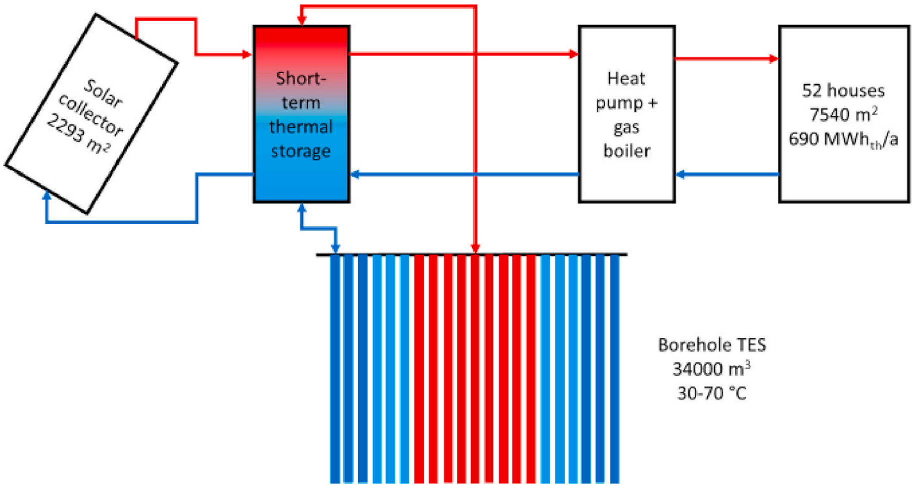

Fig. A.3. Schematic of BTES in Okotoks, Canada (adapted from Ref. [146]).

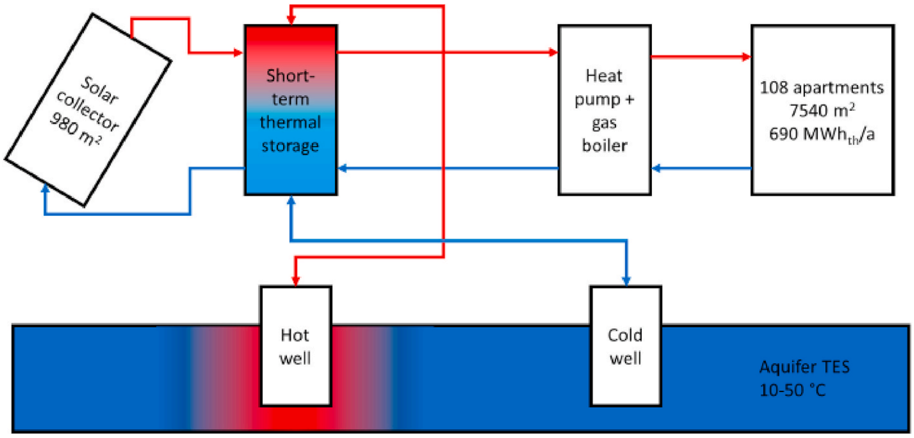

Fig. A.4. Schematic of ATES in Rostock, Germany (adapted from Ref. [60]).

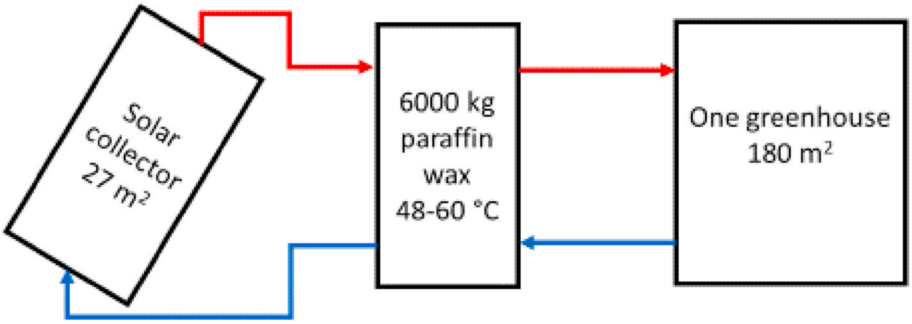

Fig. A.5. Schematic of LHS in Çukurova, Turkey (adapted from Ref. [68]).

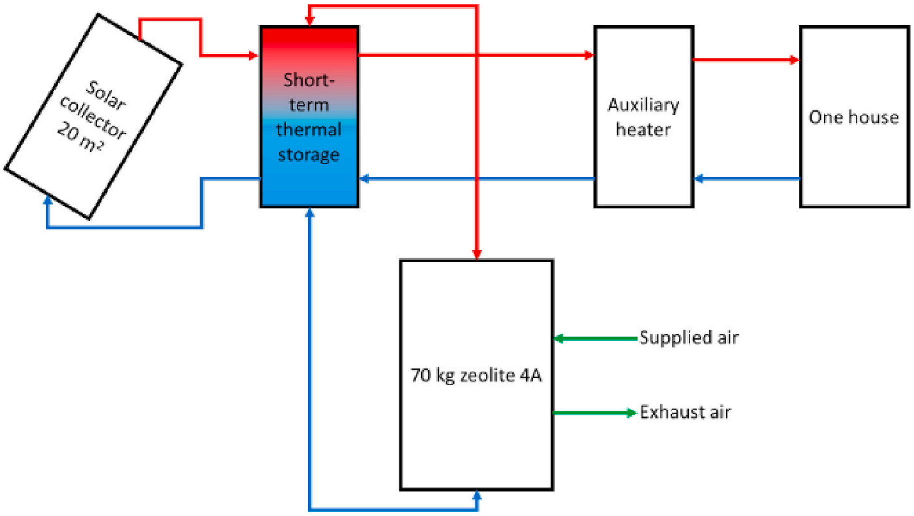

Fig. A.6. Schematic of THS in Stuttgart, German (adapted from Ref. [71]).

Table A.1
Technical review of reference SHS projects.

Project	Year of initial operation	Heated living area (m^2)	Temperature (storage/heating) (°C)	Annual heat demand (MWh_{th})	Solar collector area (m^2)	Storage volume (m^3)	Storage capacity (MWh_{th})	COP (HP/system)	HP capacity (MW_{th})	No. of storage cycles per year	Main heat source fraction (%)	Storage efficiency (%)	Reference
TTES													
Lisse, NL	1995	–	25-80/-	1583	1200	1000	–	–	–	–	–	–	[26]
Friedrichshafen, DE	1996	23,000	40-85/-	2423	2700	12,000	–	–	–	–	27	69	[27,45]
Breda, NL	1996	–	<85/-	1883	2400	5000	–	–	–	–	45	–	[26]
Hannover, DE	2000	–	–	–	1473	2750	160	–	–	–	39	–	[28]
Munich, DE	2007	30,000	10-90/55	2300	3600	5700	480	1.7/-	1.4	1–2	40–50	81	[29,131]
Gaziantep, TR	2010	100	7-35/-	10	20	300	–	5.9/-	–	–	83	–	[30]
Stockholm, SE	2013	–	25-40/30-35	8.9	50	250	–	4.25/-	–	–	92	–	[31]
Copenhagen, DK	2017	–	<95/50	1.7	2.36	0.255	–	–	–	–	50	–	[32]
Marseille, FR	2017	–	<85/50	2.65	4.5	0.3	–	–	–	–	75.4	–	[33]
Marseille, FR	2017	–	<85/60	53.52	100	3	–	–	–	–	79.9	–	[34]
Jincheon, KR	2017	214,696	40-90/50	1356	1600	2000	–	–	–	–	42.8	–	[35]
Marseille, FR	2018	1465	-/30-60	63	120	200	–	–	–	–	91	86	[36]
Panningen, NL	2021	300,000	20-90/55	28,333	20,600	121,100	28,268	-/5	2.76	1.23	41	96	[37]
PTES													
Stuttgart, DE	1986	–	0-30/40-50	97.3	211	1050	–	2.76/-	0.066	–	62	82	[38]
Ottrupgaard, DK	1996	–	-/50-70	453	562	1500	–	–	–	–	16	–	[39,40]
Steinfurt, DE	1998	3800	30-90/-	325	510	1600	–	–	–	–	34	–	[11,104]
Chemnitz, DE	2000	4680	<85/-	573	540	8000	310	–	–	–	30	–	[11,28]
Eggenstein, DE	2008	12,000	–	–	1600	4500	–	–	0.06	–	65	–	[41]
Osijek, HR	2013	400,000	85-90/21	64,000	0	30,350	–	-/0.7	–	–	3.7	80	[42]
Marstal, DK	2013	–	25-50/75	33,300	33,300	75,000	6000	3.5/-	1.5	1.26	50	55	[43,132]
Dronninglund, DK	2014	–	12-86/60-75	36,169	37,573	60,000	5100	1.66/-	2.1	2	33.6	78	[44]
BTES													
Neckarsulm, DE	1997	–	–	1891	5007	63,300	–	–	–	–	39	65	[45]
Anneberg, SE	2002	9000	30-45/32-55	1080	3000	60,000	–	–	–	–	60	58	[46]
Okotoks, CA	2007	7540	30-70/37-55	650	2293	34,000	–	-/30	–	–	93	54	[47,147]
Harbin, CN	2008	500	3.4–7.7/27.1	–	50	–	–	4.29/6.14	0.0037	–	49.7	76	[48]
Emmaboda. SE	2010	–	40-45/-	8500	0	–	–	–	–	–	18	72	[49]
Shanghai, CN	2012	2304	15–37.4/23.6–50	115	500	4970	–	-/8.7	–	–	50.6	62.9	[50]
Brædstrup, DK	2012	–	12-60/80	40,000	18,600	19,000	400	2.9/-	1.2	1.11	16.5	37	[51,132]
Tianjin, CN	2013	27,000	8–10.3/43.2	2932	1500	–	133	4.22/3.07	–	0.49	–	–	[52]
Torino, IT	2014	–	–	0.26	5	180	–	–	–	–	46	–	[53]
Andalusia, ES	2016	23,581	–	1044	1150	18,000	375	–	–	0.6	75	60	[54]
Ontario, CA	2017	4000	40-70/50	930	2009	19,500	–	3.3/2.9	–	–	70	32	[55]
Aberdeen, GB	2019	7540	–	624	2293	34,000	–	–	–	–	78	42	[56]
Camborne, GB	2019	7540	–	426.4	2293	34,000	–	–	–	–	65	20	[56]
ATES													
Scarborough, CA	1984	30,470	4-50/-	5920	0	530,000	–	5-6/-	–	–	46	–	[57]
Berlin, DE	1999	57,600	20-70/45	16,000	0	–	–	–	–	–	13	77	[58]
Brasschaat, BE	2000	–	8-18/45	–	0	–	–	5.6/-	–	–	46	–	[59]
Rostock, DE	2000	7000	10-50/45-65	622	980	20,000	–	4.5/-	–	–	49	48	[60]
Neubrandenburg, DE	2005	–	65-85/-	18,125	0	–	–		–	–	42.6	46	[61]
Adana, TR	2005	360	35/25	108	0	–	–	–	–	–	78	–	[62]
Tehran, IR	2013	12,800	43-65/60	528	–	35,387	–	-/19.6	–	–	–	63	[63]
Groningen, NL	2020	–	-/95	50,283	0	–	27,594	–	–	0.41	95	70	[64]

Table A.2
Technical review of reference LHS projects.

Project	Year of initial operation	Heated living area (m^2)	Annual heat demand (MWh$_{th}$)	Solar collector area (m^2)	Storage material	Melting temperature (°C)	Heat of fusion (kJ/kg)	Storage volume (kg)	Storage capacity (kWh$_{th}$)	Main heat source fraction (%)	Storage efficiency (%)	Reference
Biot, FR	1985	176	–	–	$CaCl_2{\cdot}6H_2O$	21	150	2105	87.7	–	–	[65]
Trabzon, TR	1992	75	20	30	$CaCl_2{\cdot}6H_2O$	29.7	187.49	1090	–	60	40	[66]
Reading, UK	1997	13.5	–	–	Salt mixture	8	216	–	–	30	–	[67]
Çukurova, TR	2003	180	–	27	Paraffin wax	48–60	190	6000	317	–	40.4	[68]
Elazıg, TR	2005	–	–	11.9	$CaCl_2{\cdot}6H_2O$	29	187.49	300	15.6	18–23	–	[69]
Lyngby, DK	2015	130	3.63	22.4	Sodium acetate trihydrate	58	265	200	–	80	–	[70]

Table A.3
Technical review of reference THS projects.

Project	Year of initial operation	Heated living area (m^2)	Solar collector area (m^2)	Storage material	Sorbate vapor pressure (mbar)	Charging temperature (°C)	Discharging temperature (°C)	Energy density (kWh$_{th}$/m^3)	Maximum power (kW$_{th}$)	COP (HP/ system)	Storage efficiency (%)	Reference
Open system												
Stuttgart, DE	2006	–	20	70 kg zeolite 4A	12	170	20	120	1.5	–	–	[71]
Petten, NL	2012	–	–	17 L $MgCl_2{\cdot}6H_2O$	12	130	60	138.9	0.15	-/12	–	[72]
Perpignan, FR	2014	–	–	400 kg $SrBr_2$	10	80	25	203	0.8	–	–	[73]
Petten, NL	2014	–	–	150 kg zeolite 13X	12	185	25–60	62	0.4	–	>60	[74]
Wels, AT	2014	–	–	53 kg zeolite 4A	10	180	25	148	1.5	-/12	–	[75]
				50 kg zeolite Na-MSX		230		154				
Villeurbanne, FR	2015	100	–	80 kg zeolite 13X	10	180	20	185	2.25	–	53	[76]
Eindhoven, NL	2017	100	–	250 L zeolite 13X	13.5	180	13	216	4.4	–	76.4	[77]
Loughborough, GB	2018	–	8	4426 kg $MgSO_4$	–	150	–	828	–	–	–	[78]
Closed system												
Högskolan Dalarna, SE	2005	–	–	54 kg LiCl salt	–	40–85	25	85	8	–	–	[71]
Rapperswil, CH	2008	–	–	7 kg zeolite 13X	23.4	180	22	57.8	0.8	–	–	[71]
Gleisdorf, AT	2008	100	–	200 kg silica gel	–	88	16–38	33.3	1	–	–	[71]
Dübendorf, CH	2008		–	160 kg NaOH	–	95	10	5	1	–	–	[71]

Table A.4
Data sources of LCOH and storage volume/capacity cost analysis.

Project	Reference	Initial investment (€)				Annual O&M cost (€)	
		Renewable energy input	Thermal storage	Back-up heating device	Overall system	Renewable energy input	Thermal storage
TTES							
Hannover, DE	[28]	–	887897.49	–	–	–	–
Munich, DE	[29,131]	–	1038209.01	–	–	–	–
Copenhagen, DK	[32]	688.39	1387.05	–	4109.77	6.88[a]	–
Marseille, FR	[33]	2392.95	936.37	–	4889.94	23.93[a]	–
Marseille, FR	[34]	33986.11	14565.77	–	72828.86	339.86[a]	–
Jincheon, KR	[35]	589821.52	280372.91	87954.02	2178601.32	5898.22[a]	2803.73[a]
Marseille, FR	[36]	115338.2	21625.91	48400.85	185364.96	1153.38[a]	216.26[a]
Panningen, NL	[37]	767,000	19,400,000	6,250,000	65,155,979	15,340	60,000
PTES							
Steinfurt, DE	[104]	677968.06	730849.57	–	–	–	–
Chemnitz, DE	[11,28]	–	840368.76	–	–	–	–
Eggenstein, DE	[28]	–	508608.15	–	–	–	–
Osijek, HR	[42]	58138034.84	1764678.43	0	76826847.42	5540494.29	12289.72
Marstal, DK	[43,132]	10162852.39	2744814.7	7967000.63	24123402.25	40330.48	28151.95
Dronninglund, DK	[44]	6784712.48	2378446.98	3694604.2	14701424.22	67847.12[a]	23784.47[a]
BTES							
Anneberg, SE	[46]	443075.43	165414.83	74436.67	1084648.64	4430.75[a]	1654.15[a]
Okotoks, CA	[47,133]	996955.56	542203.9	–	2960258.4	9969.56[a]	5422.04[a]
Shanghai, CN	[50]	–	–	0	229857.26	–	–
Brædstrup, DK	[51,132]	4141983.34	321368.21	818734.05	6495376.42	41419.83[a]	3213.68[a]
Tianjin, CN	[52]	186693.68	–	–	1581310.44	1866.94[a]	–
Andalusia, ES	[54]	461300.52	154826.1	135522.85	1407995.47	4613.01[a]	1548.26[a]
Ontario, CA	[55]	716076.91	320791.05	0	1036867.96	7160.77[a]	3207.91[a]
Aberdeen, GB	[56]	860932.97	491265.93	44273.63	2156794.51	8609.33[a]	4912.66[a]
Camborne, GB	[56]	860932.97	491265.93	44273.63	2156794.51	8609.33[a]	4912.66[a]
ATES							
Brasschaat, BE	[59]	0	632723.45	67844.47	1025041.48	0	6327.23
Rostock, DE	[60]	505744.1	246727.25	75874.97	1360139.05	5057.44	2467.27
Adana, TR	[62]	0	–	0	18182.73	0	–
Groningen, NL	[64]	–	1,480,883	–	–	–	14,809[a]
LHS							
Çukurova, TR	[68,134]	–	–	0	11348.75	–	–
Elazıg, TR	[69]	–	2310.61[b]	–	–	–	–
THS							
Stuttgart, DE	[71]	–	1977.40[b]	–	–	–	–
Loughborough, GB	[78]	494.06	2047.27	0	8237.03	–	–
Högskolan Dalarna, SE	[71]	–	2758.61[b]	–	–	–	–
Rapperswil, CH	[71]	–	3065.52[b]	–	–	–	–
Gleisdorf, AT	[71]	–	9116.58[b]	–	–	–	–
Dübendorf, CH	[71]	–	332.10[b]	–	–	–	–

Annual O&M cost (€)		Annual heat production (MWh_{th})				Lifetime (years)	Cost of storage (€)	Storage volume (m^3)	Storage capacity (MWh_{th})
Back-up heating device	Overall system	Renewable energy input	Thermal storage	Back-up heating device	Overall system				
TTES									
–	–	–	–	–	–	–	887897.49	2750	160
–	–	–	–	–	–	–	1023370	5700	480
–	143.84[a]	0.85	–	–	1.7	30	1387.05	0.26	–
–	171.15[a]	2	–	–	2.65	20	936.37	0.3	–
–	2549.01[a]	42.78	–	–	53.55	20	14565.77	3	–
166790.73[a]	175492.67	790	290	420	1356	20	280372.91	2000	–
1830.36[a]	3295.38	64	11.4	5	63	30	21625.91	200	–
–	100,000	–	–	–	28,333	50	19,400,000	121,100	28,268
PTES									
–	–	110	–	–	325	–	730849.57	1600	–
–	–	169	–	–	573	–	840368.76	8000	310
–	–	–	–	–	–	–	508608.15	4500	175
0	5708527.58	242,100	2397	0	244,497	14	1764678.43	30,350	–
891032.17	990101.68	14,326	4445	25,087	33,300	20	2744814.7	75,000	6000
422918.25[a]	514549.85[a]	16,840	10,338	25,518	36,169	20	2378446.98	60,000	5100
BTES									
31133.43[a]	37218.34	1200	650	430	1080	25	165414.83	60,000	–
–	103609.04[a]	998	341	–	764	25	542203.9	34,000	–
0	8045[a]	–	–	0	115	25	–	–	–
182704.66[a]	227338.17[a]	6881	163	2600	9200	20	321368.21	19,000	400
–	50881.94	–	66	–	1472	25	–	–	133
38875.83[a]	45037.1	1007	225	292	1044	30	154826.1	18,000	375
0	36290.38[a]	920	128	0	930	25	320791.05	19,500	–
24947.24[a]	38469.23	722	139	222	624	25	491265.93	34,000	–
18553.29[a]	32075.27	889	111	111	426.4	25	491265.93	34,000	–
ATES									
36001.82	42329.05	0	1142	1081	1335	25	632723.45	–	–
40080.15	47604.87	456	143	318	593	20	246727.25	20,000	–
0	2969.85	0	–	0	84	25	–	–	–
–	–	47,785	11,389	–	50,283	15	1,480,883	–	27,594
LHS									
0	397.21	–	–	–	4.3	12	–	11.6	0.32
–	–	–	–	–	–	–	2310.61[b]	1.67	0.016
THS									
–	–	–	–	–	–	–	1977.40[b]	0.54	0.012
0	288.3	–	–	0	4.26	30	2047.27	1.66	1.37
–	–	–	–	–	–	–	2758.61[b]	0.64	0.035
–	–	–	–	–	–	–	3065.52[b]	1.2	0.001
–	–	–	–	–	–	–	9116.58[b]	1.7	0.013
–	–	–	–	–	–	–	332.10[b]	1.3	0.0089

Table A.5
LCOH after normalization.

Project	LCOH (€/MWh_{th})	Reason	Normalized LCOH (€/MWh_{th})
TTES			
Marseille, FR	243.56	Overpriced solar collectors (961 €/m^2 while average: 361 €/m^2)	179.92
Panningen, NL	130.01	Low-priced solar collectors (37 €/m^2 while average: 361 €/m^2)	228.15
BTES			
Anneberg, SE	105.77	Low-priced borehole (2.8 €/m^3 while average: 15.6 €/m^3) and low-priced solar collectors (148 €/m^2 while average: 361 €/m^2)	182.09
Okotoks, CA	410.72	Pursuit of excessive main heat source fraction (93% while average: 52%)	229.65
Brædstrup, DK	81.19	Low share of heat discharged from storage in annual heat demand (2% while average: 31%)	245.47
Tianjin, CN	110.84	Low share of heat discharged from storage in annual heat demand (2% while average: 31%) and low-priced solar collectors (124 €/m^2 while average: 361 €/m^2)	245.47
Andalusia, ES	130.8	Low-priced borehole (8.6 €/m^3 while average: 15.6 €/m^3)	146.93
Aberdeen, GB	307.05	Oversized project scale (ratio of solar collector area to heat production: 3.7 m^2/MWh_{th} while average: 2.3 m^2/MWh_{th})	190.87
Camborne, GB	434.35	Oversized project scale (ratio of solar collector area to heat production: 5.4 m^2/MWh_{th} while average: 2.3 m^2/MWh_{th})	185
ATES			
Rostock, DE	263.77	Overpriced solar collectors (516 €/m^2 while average: 331 €/m^2)	228.6
THS			
Loughborough, GB	193.18	Low-priced solar collectors (62 €/m^2 while average: 361 €/m^2)	249.32

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