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OVERVIEW OF THE EXISTING HEAT STORAGE TECHNOLOGIES: SENSIBLE HEAT

Abstract
Over the past several decades, much attention has been given to the development of technologies utilizing solar energy to generate inexpensive and clean heat for heating purposes of buildings and even for electricity generation in the concentrating solar thermal power (CSTP) plants. However, unlike conventional heat-generating technologies consuming coal, natural gas, and oil, heat produced by solar energy is intermittent because it is significantly affected by daily (day-night) and seasonal fluctuations in solar insolation. This fact issues a considerable challenge to the adoption of solar energy as one of the main renewable heat sources in the future. Therefore, along with the development of the different solar technologies, the heat storage technologies have also been the focus of attention. Use of the storage devices, able to accumulate heat, enables not only enhance the performance of the heating systems based on solar energy but also make them more reliable.

This paper gives an overview of the various sensible heat storage technologies used in tandem with the fluctuating solar heat sources.

Key words: heat storage, sensible heat, solar energy.

Abbreviations:
ATES – aquifer thermal energy storage,
BTES – borehole thermal energy storage,
CHP – combined heat and power,
COP – coefficient of performance,
CSTP – concentrating solar thermal power,
GWTES – gravel-water thermal energy storage,
HDPE – high-density polyethylene,
HT – high-temperature,
HTF – heat transfer fluid,
HWTES – hot water thermal energy storage,
n/a – not available,
NREL – National Renewable Energy Laboratory,
R&D – research and development,
TES – thermal energy storage,
TFS – thermocline-filler storage,
UHP – ultra high performance.

Nomenclature:
c – heat capacity, $\frac{J}{K}$,
c_P – isobaric specific heat, $\frac{J}{kg \cdot K}$,

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dQ – infinitesimal amount of heat, J,
dT – infinitesimal change of temperature, K,
k_f – hydraulic conductivity, m/s,
T_C – absolute temperature of the cold reservoir, K,
T_f – final temperature, K,
T_H – absolute temperature of the hot reservoir, K,
T_i – initial temperature, K,
Δh – change in specific enthalpy, J,
η_t – thermal efficiency.

Introduction

Waste heat from combined heat and power (CHP) units in biogas plants and solar collectors are examples of the renewable heat sources, which can be used more efficiently when the heat storage is applied [1-4]. For example, the engine-based CHP unit has a total efficiency of up to 90%, producing about 35% of electricity and 65% of heat including around 10% of irreversible heat losses. In most biogas plants, a smaller fraction (20-40%) of the generated heat is needed for the digester heating, but the larger portion (60-80%) is considered as waste heat, which is often not used for further useful purposes and as a result wasted. As shown in [5], one of the possible solutions could be the use of the heat storage technology in biogas plants.

In the case of solar collectors installed in regions with relatively low value of solar irradiance such as Europe, use of the insulated hot water storage tanks in conjunction with the solar collectors enables to store enough hot water to cover all of the hot water requirements for several overcast days in summer until the collectors are capable to renew the major heat supply [1-2]. Moreover, there is more attractive and challenging heat supply concept when heat generated from solar collectors is retained for long period of time in heat storage reservoirs in summer for its further use for heating purposes in winter, which is also referred to as seasonal or long-term heat storage [1-3].

In both cases, the significant energy savings and consequently reduction of the CO_2 emission into the atmosphere are the logical results of the heat storage implementation. That's why the heat storage can be the best solution not only from the technical but also environmental and economical points of view [1-4].

Classification of the heat storage methods

It is well known that every energy system is composed of a primary energy source (e.g. solar energy or biogas), a transformer (e.g. solar collector or CHP unit) to transform primary energy into useful form of energy, and a final energy user-appliance (e.g. a heating system, a hot water supply system or some industrial process). However in some systems, especially with renewables, so-called spatiotemporal disagreements between the energy supply and energy consumption may arise. Therefore, the primary intent of the heat storage is to minimize or totally prevent these disagreements by means of shifting the supply of thermal energy in time. Obviously, a thermal flask is an example of the simplest and most widely used conventional heat storage device in the world.

The heat storage system usually consists of:

- storage tank, which is usually heat-insulated,
- working substance, which is also known as the storage material,
- facilities for charging and discharging. In general, for charging and discharging some special heat exchangers are used,
- and some auxiliary facilities, for instance: pumps, sensors, controllers etc., to transfer heat from, e.g. solar collectors, to the storage substance, and control the charging and discharging process.

In general, two criteria define the technology and material applied to store heat: (i) the heat storage period, and (ii) needed temperature level. Regarding the heat storage period, the storage technology can be used for [1-4]:

- seasonal or long-term heat storage, when storage period is about several months,
- medium-term heat storage, when storage period is about a week,
- and short-term heat storage, when storage period is up to 24 hours.

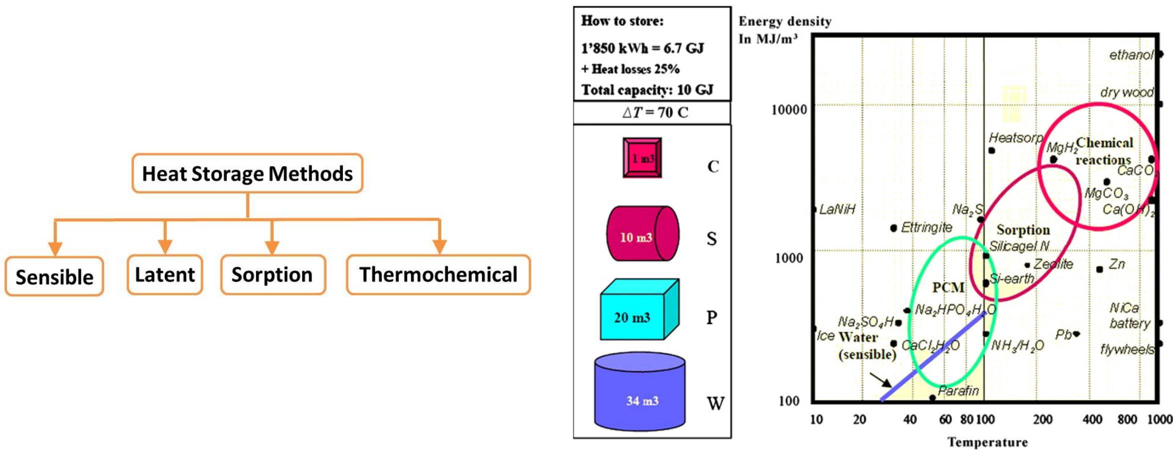
Concerning needed temperature level, the heat storage technology can be exploited for [1-4]:

- High-temperature (HT) heat storage, when the temperature of the stored heat is above 200 °C. In this case, the stored heat has the greatest energy potential and can be used as a backup heat source to support power generation in the concentrating solar thermal power plants and even some industrial processes, e.g. plastic molding, rubber and polymer vulcanization, industrial pasteurization and sterilization etc.
- Middle-temperature heat storage, when the temperature of the stored heat is above 40 °C. Such temperature level of the stored heat is particularly suitable for district heating and domestic hot water preparation.
- And for cooling applications, when the temperature of the stored heat is below 20 °C, to support air conditioning systems, refrigerators, transplants in medicine etc.

According to the system design the heat storage systems are classified as [6]:

- Direct, where the storage substance and the heat transfer fluid (HTF) are the same fluid pumped through the solar absorber and heated up on its way to the heat storage reservoir;
- Indirect, where the storage substance is located in a separate storage reservoir and another fluid transfers the solar heat from solar absorber to the storage substance by means of a heat exchanger;
- And the hybrid concept, which is a combination of direct and indirect system designs to increase flexibility and performance of the renewable energy system.

In terms of thermodynamics, heat can be stored by means of the several ways (Fig. 1, a).



(a)
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(b)

(c)
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Fig. 1. Heat storage technologies:
(a) classification of the heat storage methods;
(b) comparison of the different heat storage technologies represented in energy cubes;
(c) energy density versus working temperature ranges of the various heat storage materials.

First, sensible heat storage, when the storage substance is heated or cooled. In this case, the technology is based on the use of the specific heat of a heat storage medium. Commonly known sensible heat storage technology is an insulated hot water storage reservoir.

The phase change or phase transition of a storage substance, e.g. melting/crystallization of paraffin, consumes/release a large amount of heat without temperature change. Therefore, in this case, the heat required to melt substance is called latent. The latent heat storage technology can provide higher storage capacity than the sensible heat storage at practically constant charging-discharging temperature.

Heat can also be stored by reversible chemical reactions and sorption physicochemical processes. Both of the storage methods can achieve the highest storage capacities compared with the sensible and latent heat storage, and they also are able to absorb and release heat at constant charging-discharging temperatures, depending on the thermochemical reaction or sorption physicochemical process.

Fig. 1 (b) illustrates a comparison of the different heat storage technologies, especially: sensible, latent, sorption and thermochemical heat storages, represented in the energy cubes. From this picture, it can be seen that in order to store 10 GJ of heat, generated by e.g. solar collectors, 34 cubic meter hot water reservoir is necessary. On the other hand, if a phase change material, e.g. paraffin, is used instead of water only 20 cubic meters of the storage material is required to store the same heat amount. And finally, if the sorption or thermochemical heat storage technologies are applied the volumes of the heat storage substances can be reduced up to 10 and 1 cubic meter respectively. That is to say, that in terms of theoretical values of the heat storage capacities as well as material consumption and the space needed for the storage reservoir the thermochemical heat storage promises the storage of the future. At the same time, as shown in Fig. 1 (c), the four heat storage technologies mentioned above are usually applied at different working temperature ranges. Thus, for low-temperature heat storage of up to 100 °C, water, and phase change materials are exploited. Sorption heat storage is appropriate to store medium heat. And finally, for HT heat storage, e.g. in CSTP plants, reversible chemical reactions are the most suitable.

Thermodynamics of the sensible heat storage

Sensible heat storage is based on the use of the heat capacity of a storage substance to retain the thermal energy. The heat capacity *c* is defined as a ratio of the infinitesimal amount of heat *dQ*, which is added to the substance, to the infinitesimal increase of temperature *dT*:

$$c = \frac{dQ}{dT}. \tag{1}$$

The heat capacity indicates how much thermal energy *dQ* a storage substance can accumulate in a temperature change *dT*.

According to the first law of thermodynamics, in the isobaric process the specific heat quantity, which can be accumulated in the mass unit of a storage substance, can be calculated as follows:

$$q = \Delta h = \int_{T_i}^{T_f} c_p \cdot dT, \tag{2}$$

where Δh – change in specific enthalpy of a storage substance, T_i – initial temperature, T_f – final temperature, c_p – isobaric specific heat.

If the specific heat is constant, then specific heat quantity is just multiplication of the average isobaric specific heat c_P and temperature change ($T_f - T_i$):

$$q = \Delta h = c_p \cdot (T_f - T_i). \tag{3}$$

Hot water storage

Table 1 shows thermophysical properties of some of the common materials/substances, which are currently used or can be potentially applied for sensible heat storage.

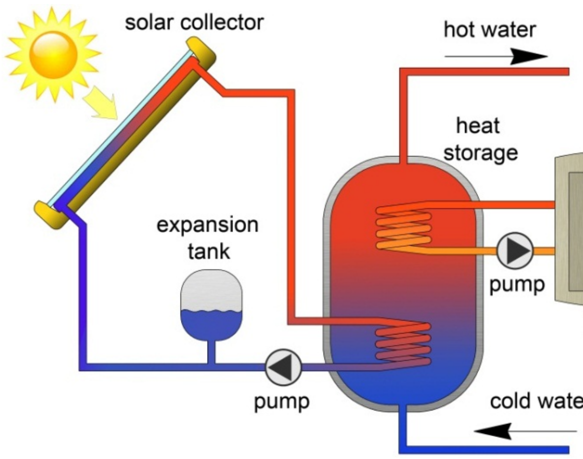
The table shows that among conventional storage media, water has the highest value of the specific heat of app. 4182 $\frac{J}{kg \cdot K}$ at 20 °C, what is more than 4 times higher than for other materials. This positive feature helps to make the heat storage system based on the water more compact. Moreover, water possesses high fluidity, which enables to use it along with the conventional pumps and heat exchangers both as a heat storage substance and HTF. Additionally, in the economic point of view, water is the most inexpensive substance to store the low-temperature heat of up to 100 °C, which is particularly suitable for domestic applications. Therefore, as shown in [9], the heat storage market is largely ruled by the hot water storage technology.

Table 1. Thermophysical properties of some of the common used sensible heat storage media at 20 °C

Material	Specific heat, $\frac{J}{kg \cdot K}$	Density, $\frac{kg}{m^3}$	Heat Conductivity, $\frac{W}{m \cdot K}$	Source
Water	4182	998.2	0.602	[10, 11]
Soil (wet)	2093	1700	2.51	[14]
Soil (dry)	795	1260-1300	0.25-0.3	[14, 15]
Clay	860-880	1500-2300	0.7-1.5	[15]
Sand	754-796	1700	0.35	[12, 16]
Granite	600-950	2640-2760	1.73 to 3.98	[12, 14, 15]
Marble	800-883	2600-2840	2.07 to 3.2	[12, 15]
Limestone	741-921	2500-2760	1.26-2.2	[12, 13, 14]
Sandstone	694-950	2200-2600	1.7-2.9	[13, 15]
Lime-and-sand brick	837-879	1800	0.7	[12, 16]
Brick magnesia	1130-1150	3000	5.0-5.1	[15]
Silica fire brick	1000	1800	1.5	[15]
Slag	840	2700	0.6	[15]
Graphite	401-610	2200-2300	122-155	[15]
Cast iron	465-837	7200-7900	29.3-73.0	[14]

Source: Author's

To sustain heating and hot water supply system, insulated hot water storage vessels are the most applicable. Fig. 2 (a) illustrates the solar hot water supply system where the solar loop filled with antifreeze is separated by a heat exchanger from the storage medium (water) within the storage reservoir. Here, a pump conveys the antifreeze through the solar collector, where it is heated and then the solar heat is transferred to the water by means of the heat exchanger. If solar insolation is not high enough, the conventional boiler is triggered to heat up water up to the appropriate temperature level. The system can also be used to provide not only hot water but also heating. The heat exchanger of the solar loop is usually installed at the bottom of the hot water storage reservoir, while the heat exchanger of the boiler at the top. This arrangement allows sustaining the temperature stratification within the tank.



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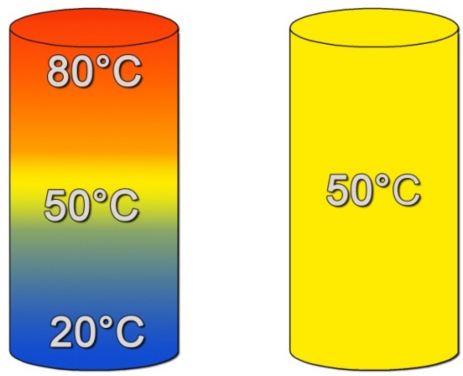


(b)
Source: [17]

Fig. 2. Solar hot water supply system:
(a) scheme of the solar hot water supply system with a hot water storage tank;
(b) two types of the thermal stratification within the tank with the same amount of stored heat: left – fully stratified hot water storage tank, right – unstratified fully mixed hot water storage tank.

According to Henninger S. [16], currently, modern hot water storage vessels combine several specific features, which improve the overall efficiency of storing solar heat, including:

- the small number of thermal bridges around the storage vessel, in order to reduce the heat losses,
- enhanced heat insulation for example by using vacuum insulation,
- siphon introductions of pipes to avoid natural convection losses,
- stratification enhancers to increase the exergy value of the content of the store,

- internal devices to reduce the speed of inlet water not to disturb stratification inside the storage vessel,
- and, large heat exchangers or mantle heat exchangers.

As shown in [18-22], since the end of the 1960ies, enhancement of the thermal stratification within the solar hot water storage tanks was the focus of the R&D attention. The vertical thermal stratification is a natural process occurring over time in an undisturbed hot water tank due to the heat losses through the external walls, which in turn initiate dynamics of water due to the density difference between cold and hot water regions.

Fig. 2 (b) illustrates two types of the vertical thermal stratification within the hot water storage tanks with the same amount of stored heat.

In thermodynamics point of view, the thermal stratification increases considerably the thermal efficiency of the hot water storage tank as given by the Carnot's formula:

$$\eta_t = 1 - \frac{T_C}{T_H}, \quad (4)$$

where η_t – thermal efficiency; T_C – the absolute temperature of the cold reservoir; T_H – the absolute temperature of the hot reservoir.

Thus, the higher temperature difference between hotter and colder water regions within the hot water storage tank, the higher the thermal efficiency of the heat stored is. Moreover, compared to some conventional media, such as bricks, glass, and soil, the not disturbed water is relatively poor heat conductor.

According to Gang Li et al. [23], based on a comparison between the fully stratified water tank and fully mixed water tank (Fig. 2, b) employed in many solar systems, the energy storage efficiency and the whole system efficiency of the former one may increase up to 6% and 20% respectively. For the seasonal TES, the average net energy and exergy efficiencies can even be improved by 60%.

Moreover, as shown in [17], thermal stratification within the storage tank results in longer operation hours of the solar collectors and thus their significantly larger utilization and thereby reduction in the use and cost of auxiliary energy.

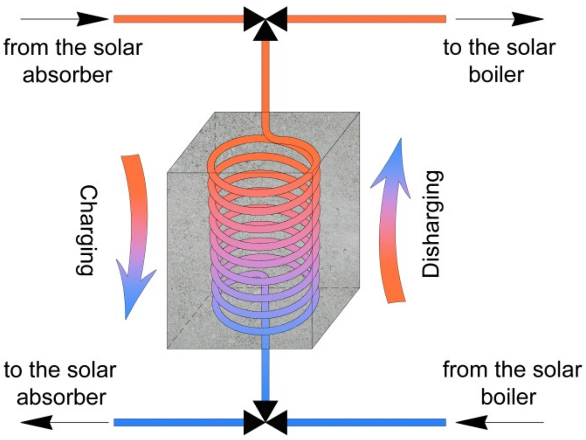
High-temperature heat storage with solid materials and molten salts

Despite some positive features of water as the sensible heat storage substance, it has an upper-temperature limit of around 100 °C only, which makes the HT heat storage for CSTP or industrial applications with water impossible. Therefore, among other sensible heat storage substances, various types of molten salts and rocks including concrete, castable ceramics and bricks are employed.

At the first blush, concrete is a very durable material. However, as shown in [24] typical structural concrete explodes violently in the temperature range between 200 °C and 300 °C. Therefore, different types of concrete and castable ceramics with improved properties were developed to allow a heat storage system operate in HT range of 500 °C-565 °C suitable for CSTP plants, industrial waste heat recovery, thermal management of decentralized CHP systems and other HT processes [25].

There are two basic concepts established to store HT heat in solid materials such as concrete, castable ceramics and natural rocks. First one is so-called passive storage concept where heat exchangers are embedded inside modular blocks of concrete or ceramics and HT fluid, usually thermal oil, molten salt or air, is pumped through them to transfer HT heat to and from the solid medium. Fig. 3 (a) illustrates the conceptual design of concrete heat storage and Fig. 3 (b) shows an actual example of the passive concept application represented with HT concrete storage in CSTP plant.

The wide range of possible operational temperatures (up to 600 °C), the modular structure of the store and environmental friendliness of the technology are obvious advantages what will enable the concrete heat storage to be the storage technology of the future, especially for CSTP plants.



(a)
Source: Author's

(b)
Source: [26]

Fig. 3. Illustration of the HT heat storage in concrete and castable ceramics:
(a) Passive HT heat storage concept in concrete;
(b) Example of the passive HT heat storage concept applied at Plataforma Solar de Almería (Spain).

Table 2 shows a list of operational CSTP plants and those, which are under construction, with the concrete and ceramic materials applied to store HT heat.

Table 2. List of CSTP plants with the concrete and ceramics heat storage

Name of the CSTP Project, Country	Type of Technology Applied	Type of the Heat-Transfer Fluid	Solar-Field Inlet Temperature, °C	Solar-Field Outlet Temperature, °C	Description	Storage Capacity, hours
Zhangjiakou 50MW CSG Fresnel project, China	Linear Fresnel reflector	Water/Steam	n/a	n/a	Solid state formulated concrete	14
Zhangbei 50MW CSG Fresnel CSP project, China	Linear Fresnel reflector	Water/Steam	n/a	n/a	Solid state formulated concrete	14
Jülich 1.5 MW Solar Tower, Germany	Power tower	Air	n/a	680	Ceramic heat sink	1.5

Source: [27]

The main issue of the passive storage concept is that metallic materials usually applied to manufacture the heat exchangers have higher average value of the thermal expansion coefficient compared to concrete or ceramics, for instance $17.5 \cdot 10^{-6}$ 1/°C for 316 stainless steel [28] versus $11.8 \cdot 10^{-6}$ 1/°C and $9.3 \cdot 10^{-6}$ 1/°C for castable ceramics and HT concrete at 350 °C respectively [26]. Thus, if a material for the heat exchanger design is incorrectly selected, this will induce an intensive cracking in solid concrete blocks when heated due to the temperature stresses at the interface between the concrete material and heat exchanger. Ultimately, this will lead to the reduction of the heat storage performance. As shown in [29, 30], possible solution of this problem could be an incorporation of a soft material such as Teflon tape between concrete and tubes of the heat exchanger, which reduces considerably the stresses at the interface preventing cracking of the concrete blocks and allowing heat transfer between heat exchanger and the concrete media.

Thermo-physical properties of the different types of concrete and ceramics are presented in Table 3. In contrast to the passive concept, so-called thermocline TES system has shown good ability to store HT heat.

There are several concepts of the thermocline TES developed in recent years, such as the single tank with floating barrier [31], single tank with embedded heat exchanger [32], and the thermocline-filler storage (TFS). However, among these three concepts, the thermocline-filler storage (TFS) developed by Sandia National Laboratories [33, 34] is the most promising since it allows to use inexpensive and durable solid filler material, such as concrete, sand or natural rocks, replacing about 50-75% of the costly molten salt. Moreover, in this type of the thermocline TES system, hot air can be applied instead of molten salt as HTF.

Table 3. Thermophysical properties of concrete and castable ceramics for HT heat storage

Material	**Density, $\frac{kg}{m^3}$**	**Heat Conductivity at 20 °C, $\frac{W}{m \cdot K}$**	**Specific heat at 20 °C, $\frac{J}{kg \cdot K}$**	**Source**
HT concrete	2800	1.0	916	[15]
UHP concrete	2100-2300	1.65-2.52	800-950	[24]
High alumina concrete	2400	0.2	980	[15]
Reinforced concrete	2200	1.5	850	[15]
Castable ceramics	3500	1.4	866	[15]
Alumina ceramics	3800-4000	18.0-33.0	755-880	[15]
Silicon carbide ceramics	3200	120.0	750	[15]

Source: Author's

Here (Fig. 4, a), the system operates similarly to the stratified hot water storage reservoir but instead of water HT fluid is used as HTF being in direct contact with the solid filler [34-41]. This allows: (i) to dispense with costly stainless steel heat exchanger because HTF is in direct contact with the filler, (ii) to increase heat transfer rate since molten salt or air transfers heat directly to the solid material eliminating use of the heat exchanger, (iii) to create vertical thermal stratification within the storage container and thus increase the exergy value of the content of the store, (iv) use one container only instead of two containers, which significantly reduces cost of the storage system. It was also estimated by Sandia, that the cost reduction potential is to be about 20-37% [33, 34].

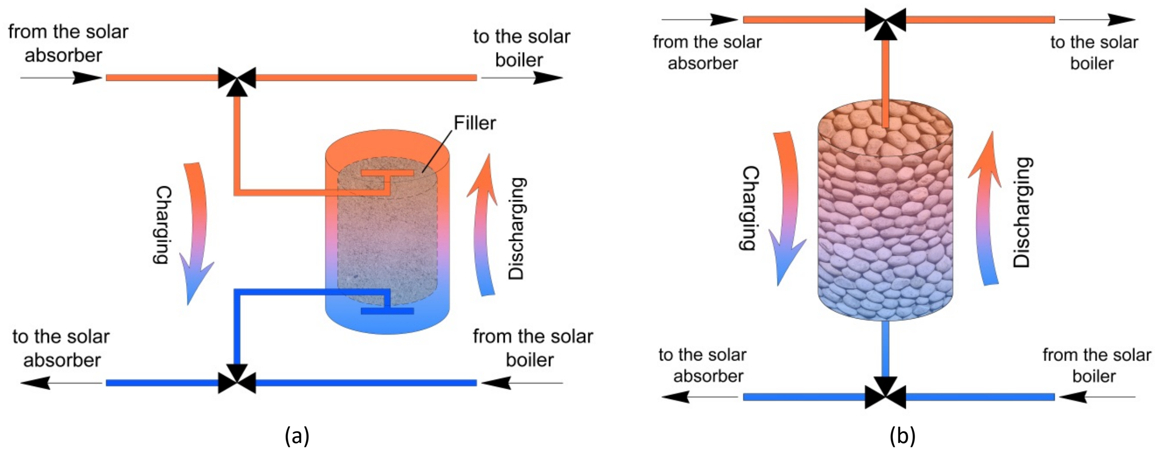


Fig. 4. Illustration of the thermocline HT heat storage concepts:
(a) thermocline heat storage concept with molten salt and UHP concrete filler;
(b) thermocline heat storage concept with molten salt or hot air and natural rock filler.

Source: Author's

However, the main problem of the thermocline HT heat storage is that filler stays always in direct contact with the corrosive hot molten salt mixture, which makes a demand to the chemical resistivity of the solid filler. Therefore, currently, many R&D efforts are made with the purpose to develop the filler, which will satisfy the requirements for chemical resistivity. One of the examples is so-called ultra-high performance (UHP) concrete able to be used in the corrosive environment and at high temperatures [24].

Recent studies [15] also showed that some natural rocks such as dolerite, granodiorite, hornfels, gabbro and quartzitic sandstone can be used as very promising and inexpensive storage materials for large-scale air-based CSTP systems equipped with packed rock bed heat storage containers.

Thermo-physical properties of these promising natural rocks are presented in Table 4.

Table 4. Thermophysical properties of the promising natural rocks suitable for HT heat storage

Material	**Density, $\frac{kg}{m^3}$**	**Heat Conductivity at 20 °C, $\frac{W}{m \cdot K}$**	**Specific heat at 20 °C, $\frac{J}{kg \cdot K}$**
Granodiorite	2700	2.1-2.6	650-1020
Gabbro	2900-3000	1.5-2.6	600-1000
Hornfels	2700	1.5-3.0	820
Quartzitic sandstone	2600	5.0-5.2	652
Dolerite	2700-2900	2.2-3.0	870-900

Source: [15]

As shown in [15, 42-51], HT heat storage in packed rock bed employed in air-based CSTP plants has some technical and economic advantages over other HT heat storage technologies: (i) low investment cost, (ii) high heat transfer rate because of the direct contact between HTF and rocks, (iii) higher efficiency because costly heat exchanger separating solar loop filled with HTF from storage container in not needed, (iii) simple and compact storage unit. Principal scheme of the packed rock bed is illustrated in Fig. 4 (b).

Table 5 shows a list of operational CSTP plants with the packed rock bed heat storage system. However, since it is the relatively new concept design for HT heat storage, which is still under development, we have found only one CSTP plant with TES system based on TFS in NREL database [27].

Table 5. List of CSTP plants based on the packed rock bed heat storage

Name of the CSTP Project, Country	**Type of Technology Applied**	**Type of the Heat-Transfer Fluid**	**Solar-Field Inlet Temperature, °C**	**Solar-Field Outlet Temperature, °C**	**Type of Rock**	**Storage Capacity, hours**
Airlight Energy Ait-Baha 3 MW Pilot Plant, Morocco	Parabolic trough	Air at ambient pressure	270	570	n/a	5

Source: [27]

Despite some benefits of the solid materials as the HT heat storage media, molten salts are widely used for large-scale HT heat storage in CSTP plants. Molten salts compared to other HT heat storage media have some benefits including excellent thermal stability at HT, low vapor pressure, low viscosity, high thermal conductivity, non-flammability, and non-toxicity. Moreover, molten salts can be designed in various chemical formulations to allow not only efficient HT heat storage at suitable temperature level but also heat transfer from the solar absorber to the storage tank and boiler.

Among different salt mixtures so-called Solar Salt, Hitec, and Hitec XL are the most widely used molten salts as the heat storage media. Thermal properties of these molten salt mixtures are represented in Table 6.

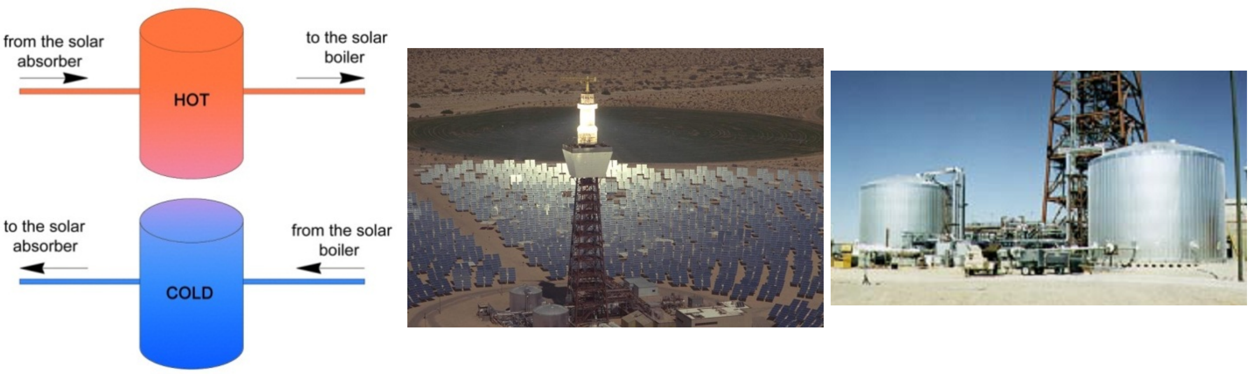
Actually, there are two concepts applied to the HT heat storage with molten salts in CSTP plants: direct and indirect. Direct storage systems (Fig. 5, a) are systems where the molten salt serves as HTF and heat storage media, hence the costly heat exchangers to transfer heat from HTF to the heat storage substance are not needed. The system consists of two molten salt storage reservoirs: one to retain enough hot molten salt after being heated in solar receiver to provide heat for water-steam cycle during cloudy periods (or even at night) when solar energy is not sufficient for steam generation by concentrating solar system; another tank to retain cold molten salt until the sun will be able to heat it up. The hot and cold molten salt storage reservoirs are installed in series to molten salt circulation in the solar cycle, before and after solar boiler respectively (see Fig. 5, a).

Table 6. Thermophysical properties of the eutectic molten salt mixtures suitable for HT heat storage

Molten Salt	**Composition, w%**	**Melting point**	**Maximum operation temperature**	**Specific heat at 300 °C, $\frac{J}{kg \cdot K}$**	**Density at 300 °C, $\frac{kg}{m^3}$**	**Viscosity at 300 °C, cp**
Solar salt	60% $NaNO_3$ + 40% KNO_3	220	585	1495	1899	3.26
Hitec	7% $NaNO_3$ + 53% KNO_3 + 40% $NaNO_2$	142	450-538	1560	1860	3.16
Hitec XL	45% KNO_3 + 7% $NaNO_2$ + 48% $Ca(NaNO_3)_2$	120	480-505	1447	1992	6.37

Source: [52]

Fig. 5, b illustrates an example of the CSTP plant with the two-tank direct heat storage applied to provide three full hours of the HT heat storage.



(a)
Source: Author's

(b)
Source: [53, 54]

Fig. 5. Illustration of the direct concept applied for HT heat storage with molten salt in CSTP plant:
(a) Two-tank direct heat storage concept;
(b) The two-tank direct molten-salt TES system at the Solar Two CSTP plant.

Table 7 shows a list of CSTP plants with HT heat storage systems based on the two-tank direct concept.

Table 7. List of CSTP plants with the 2-tank direct heat storage

Name of the CSTP Project, Country	**Type of Technology Applied**	**Type of the Heat-Transfer Fluid**	**Solar-Field Inlet Temperature, °C**	**Solar-Field Outlet Temperature, °C**	**Description**	**Storage Capacity, hours**
Archimede 5MW, Italy	Parabolic trough	Molten salt (60% $NaNO_3$, 40% KNO_3)	290	550	Total of 1,580 tons of molten salt. 60% sodium nitrate, 40% potassium nitrate. Capacity 100 MWh (thermal). Tanks are 6.5 m high and 13.5 m in diameter.	8
ASE 0.35 MW Demo Plant, Italy	Parabolic trough	Molten salt	290	550	molten salt	4.27 MWh-t
Atacama-1	Power	Molten salt	300	550	molten salt	17.5

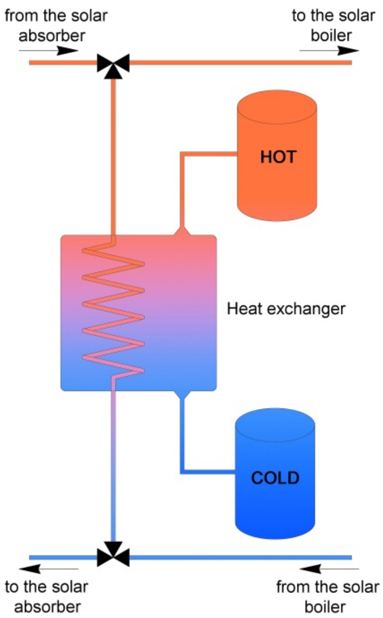
Name of the CSTP Project, Country	Type of Technology Applied	Type of the Heat-Transfer Fluid	Solar-Field Inlet Temperature, °C	Solar-Field Outlet Temperature, °C	Description	Storage Capacity, hours
110MW, Chile	tower					
Aurora 150 MW Solar Energy Project, Australia	Power tower	Molten salt	n/a	n/a	molten salt	8
Chabei 64MW Molten Salt Parabolic Trough project, China	Parabolic trough	Molten salt	n/a	n/a	molten salt	16
Copiapó 260 MW, Chile	Power tower	Molten salt	n/a	n/a	molten salt	14
Crescent Dunes 110 MW Solar Energy Project, United States	Power tower	Molten salt	288	566	TES achieved by raising salt temperature from 550 to 1050 F. Thermal storage efficiency is 99%	10
Dacheng Dunhuang 50MW Molten Salt Fresnel project, China	Linear Fresnel reflector	Molten salt	n/a	n/a	molten salt	13
DEWA 100 MW CSP Tower Project, United Arab Emirates	Power tower	Molten salt	n/a	n/a	molten salt	15
Gansu Akesai 50MW Molten Salt Trough project, China	Parabolic trough	Molten salt	n/a	n/a	molten salt	15
Gemasolar Thermosolar 19.9 MW Plant, Spain	Power tower	Molten salts (sodium and potassium nitrates)	290	565	One cold-salts tank (290 °C) from where salts are pumped to the tower receiver and heated up to 565 °C, to be stored in one hot-salts tank (565 °C). Annual equivalent hours = 5,000.	15
Golden Tower 100MW Molten Salt project, China	Power tower	Molten salt	n/a	n/a	molten salt	8
Golmud 200 MW, China	Power tower	Molten salt	n/a	n/a	molten salt	15
Hami 50 MW	Power tower	Molten salt	n/a	n/a	molten salt	8

Name of the CSTP Project, Country	Type of Technology Applied	Type of the Heat-Transfer Fluid	Solar-Field Inlet Temperature, °C	Solar-Field Outlet Temperature, °C	Description	Storage Capacity, hours
CSP Project, China						
Jemalong 1.1 MW Solar Thermal Station, Australia	Power tower	Liquid sodium	270	560	Liquid sodium	3
Likana 390 MW Solar Energy Project, Chile	Power tower	Molten salt	n/a	n/a	molten salt	13
NOOR III 150 MW, Morocco	Power tower	Molten salt	n/a	n/a	molten salt	7
Qinghai Gonghe 50 MW CSP Plant, China	Power tower	Molten salt	n/a	n/a	molten salt	6
Redstone 100 MW Solar Thermal Power Plant, South Africa	Power tower	Molten salt	288	566	molten salt	12
13.8 MW Solar Electric Generating Station I, United States	Parabolic trough	n/a	n/a	307	Storage system was damaged by fire in 1999 and was not replaced	3
SunCan Dunhuang 10 MW Phase I, China	Power tower	Molten salt	n/a	n/a	molten salt	15
SunCan Dunhuang 100 MW Phase II, China	Power tower	Molten salt	n/a	n/a	molten salt	11
Supcon 50 MW Solar Project, China	Power tower	Molten salt	n/a	n/a	molten salt	6
Tamarugal 450 MW Solar Energy Project, Chile	Power tower	Molten salt	n/a	n/a	molten salt	13
Yumen 100MW Molten Salt	Power tower	Molten salt	n/a	n/a	molten salt	10

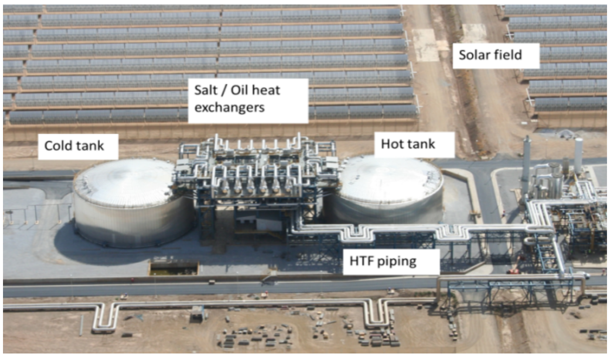
Name of the CSTP Project, Country	**Type of Technology Applied**	**Type of the Heat-Transfer Fluid**	**Solar-Field Inlet Temperature, °C**	**Solar-Field Outlet Temperature, °C**	**Description**	**Storage Capacity, hours**
Tower CSP project, China						
Yumen 50MW Molten Salt Tower CSP project, China	Power tower	Molten salt	n/a	n/a	molten salt	9

Source: [27]

Indirect storage systems (Fig. 6, a) consist of two separate storage reservoirs for hot and cold molten salt, which are connected in the parallel scheme to the solar loop. Here, HTF and heat storage media are different fluids. In the charging process, thermal oil, mostly used as HTF, transfers excess solar heat to the molten salt by means of the shell-and-tube heat exchangers, while molten salt is pumped from cold tank to the hot tank. In discharging process, e.g. at night, the hot molten salt returns back the stored heat to the thermal oil to sustain the water-steam cycle when pumped back from the hot to the cold tank.



(a)
Source: Author's



(b)
Source: [55]

Fig. 6. Illustration of the 2-tank indirect heat storage concept:
(a) Two-tank indirect heat storage concept;
(b) Two-tank indirect heat storage applied in CSTP Plant Andasol 3 (Spain).

Table 8 shows a list of the CSTP plants with HT heat storage systems based on the 2-tank molten salt indirect concept.

Table 8. List of CSTP plants with the 2-tank indirect heat storage

Name of the CSTP Project, Country	Type of Technology Applied	Type of the Heat-Transfer Fluid	Solar-Field Inlet Temperature, °C	Solar-Field Outlet Temperature, °C	Description	Storage Capacity, hours
50 MW Andasol-1, Spain	Parabolic trough	DOWTHERM A *	293	393	28,500 tons of molten salt (60% of sodium nitrate and 40% of potassium nitrate)	7.5
50 MW Andasol-2, Spain	Parabolic trough	DOWTHERM A *	293	393	28,500 tons of molten salt (60% of sodium nitrate and 40% of potassium nitrate)	7.5
50 MW Andasol-3, Spain	Parabolic trough	DOWTHERM A *	293	393	28,500 tons of molten salt (60% of sodium nitrate and 40% of potassium nitrate)	7.5
50 MW Arcosol 50 (Valle 1), Spain	Parabolic trough	Diphenyl/Diphenyl Oxide	293	393	28,500 tons of molten salt (60% of sodium nitrate and 40% of potassium nitrate)	7.5
50 MW Arenales, Spain	Parabolic trough	Diphyl	293	393	molten salt mixture (60% of sodium nitrate and 40% of potassium nitrate)	7.0
110 MW Ashalim, Israel	Parabolic trough	n/a	n/a	n/a	molten salt	4.5
50 MW Aste 1A, Spain	Parabolic trough	Dowtherm A *	293	393	molten salt mixture (60% of sodium nitrate and 40% of potassium nitrate)	8
50 MW Aste 1B, Spain	Parabolic trough	Dowtherm A *	293	393	molten salt mixture (60% of sodium nitrate and 40% of potassium nitrate)	8
50 MW Astexol II, Spain	Parabolic trough	Thermal oil	293	393	molten salt mixture (60% of sodium nitrate and 40% of potassium nitrate)	8
55 MW Bokpoort, South Africa	Parabolic trough	Dowtherm A *	293	393	molten salts	9.3 (1300 MWht)
50 MW Casablanca, Spain	Parabolic trough	Diphenyl/Biphenyl oxide	293	393	molten salt mixture (60% of sodium nitrate and 40% of potassium nitrate)	7.5
Delingha 50MW Thermal Oil Parabolic Trough project, China	Parabolic trough	Thermal oil	293	393	molten salts	9
DEWA 600	Parabolic	Thermal oil	n/a	n/a	molten salts	10

Name of the CSTP Project, Country	Type of Technology Applied	Type of the Heat-Transfer Fluid	Solar-Field Inlet Temperature, °C	Solar-Field Outlet Temperature, °C	Description	Storage Capacity, hours
MW CSP Trough Project, United Arab Emirates	trough					
100 MW Diwakar, India	Parabolic trough	Thermal oil	n/a	n/a	molten salts	4 (1010 MWht)
50 MW Extresol-1, Spain	Parabolic trough	Diphenyl/Biphenyl oxide	293	393	28,500 tons of molten salt (60% of sodium nitrate and 40% of potassium nitrate)	7.5
49.9 MW Extresol-2, Spain	Parabolic trough	Diphenyl/Biphenyl oxide	293	393	28,500 tons of molten salt (60% of sodium nitrate and 40% of potassium nitrate)	7.5
50 MW Extresol-3, Spain	Parabolic trough	Diphenyl/Biphenyl oxide	293	393	28,500 tons of molten salt (60% of sodium nitrate and 40% of potassium nitrate)	7.5
28 MW Gujarat Solar One, India	Parabolic trough	Diphyl	293	393	molten salts	9
Gulang 100MW Thermal Oil Parabolic Trough project, China	Parabolic trough	Thermal oil	n/a	n/a	molten salts	7
Huanghe Qinghai Delingha 135 MW DSG Tower CSP Project, China	Power tower	Water/Steam	n/a	n/a	molten salts	3.7
100 MW Ilanga I, South Africa	Parabolic trough	Thermal oil	293	393	molten salts	4.5
100 MW Kathu Solar Park, South Africa	Parabolic trough	Thermal oil	293	393	molten salts	4.5
100 MW KaXu Solar	Parabolic trough	Thermal oil	n/a	n/a	molten salts	2.5

Name of the CSTP Project, Country	Type of Technology Applied	Type of the Heat-Transfer Fluid	Solar-Field Inlet Temperature, °C	Solar-Field Outlet Temperature, °C	Description	Storage Capacity, hours
One, South Africa						
100 MW KVK Energy Solar Project, India	Parabolic trough	Synthetic Oil	n/a	n/a	molten salts	4 (1010 MWht)
50 MW La Africana, Spain	Parabolic trough	n/a	293	393	molten salt mixture (60% of sodium nitrate and 40% of potassium nitrate)	7.5
49.9 MW La Dehesa, Spain	Parabolic trough	Diphenyl/Biphenyl oxide	298	393	29,000 tons of molten salt (60% of sodium nitrate and 40% of potassium nitrate)	7.5
50 MW La Florida, Spain	Parabolic trough	Diphenyl/Diphenyl oxide	298	393	29,000 tons of molten salt (60% of sodium nitrate and 40% of potassium nitrate)	7.5
49.9 MW Manchasol-1, Spain	Parabolic trough	Diphenyl/Diphenyl oxide	293	393	28,500 tons of molten salt (60% of sodium nitrate and 40% of potassium nitrate)	7.5
50 MW Manchasol-2, Spain	Parabolic trough	Diphenyl/Diphenyl oxide	293	393	28,500 tons of molten salt (60% of sodium nitrate and 40% of potassium nitrate)	7.5
52 MW MINOS, Greece	Power tower	n/a	n/a	n/a	molten salt mixture (60% of sodium nitrate and 40% of potassium nitrate)	5
160 MW NOOR I, Morocco	Parabolic trough	Dowtherm A *	293	393	molten salts	3
200 MW NOOR II, Morocco	Parabolic trough	Thermal oil	293	393	molten salts	7
Rayspower Yumen 50MW Thermal Oil Trough project, China	Parabolic trough	Thermal oil	n/a	n/a	molten salts	7
50 MW Shagaya CSP Project, Kuwait	Parabolic trough	n/a	n/a	n/a	molten salts	10
Shangyi	Power	Water/Steam	n/a	n/a	molten salts	4

Name of the CSTP Project, Country	Type of Technology Applied	Type of the Heat-Transfer Fluid	Solar-Field Inlet Temperature, °C	Solar-Field Outlet Temperature, °C	Description	Storage Capacity, hours
50MW DSG Tower CSP project, China	tower					
280 MW Solana Generating Station, United States	Parabolic trough	Therminol VP-1/Xceltherm MK1	293	393	molten salts	6
49.9 MW Termesol, Spain	Parabolic trough	Diphenyl/Diphenyl Oxide	293	393	28,500 tons of molten salt (60% of sodium nitrate and 40% of potassium nitrate)	7.5
50 MW Termosol 1, Spain	Parabolic trough	Thermal oil	293	393	molten salt mixture (60% of sodium nitrate and 40% of potassium nitrate)	9
50 MW Termosol 2, Spain	Parabolic trough	Thermal oil	293	393	molten salt mixture (60% of sodium nitrate and 40% of potassium nitrate)	9
Urat 50MW Fresnel CSP project, China	Linear Fresnel reflector	Thermal oil	n/a	n/a	molten salts	6
Urat Middle Banner 100MW Thermal Oil Parabolic Trough project, China	Parabolic trough	Thermal oil	n/a	n/a	molten salts	4
100 MW Xina Solar One, South Africa	Parabolic trough	Thermal oil	n/a	n/a	molten salts	5.5
Yumen 50MW Thermal Oil Trough CSP project, China	Parabolic trough	Thermal oil	n/a	n/a	molten salts	7

* DOWTHERM A is a eutectic mixture of two very stable organic compounds, biphenyl ($C_{12}H_{10}$) and diphenyl oxide ($C_{12}H_{10}O$) [56].

Source: [27]

The data presented for CSTP plants (see Tables 2, 5, 7, 8) clearly show that currently, the molten salts are the most applicable for HT heat storage.

Seasonal heat storage with sensible materials

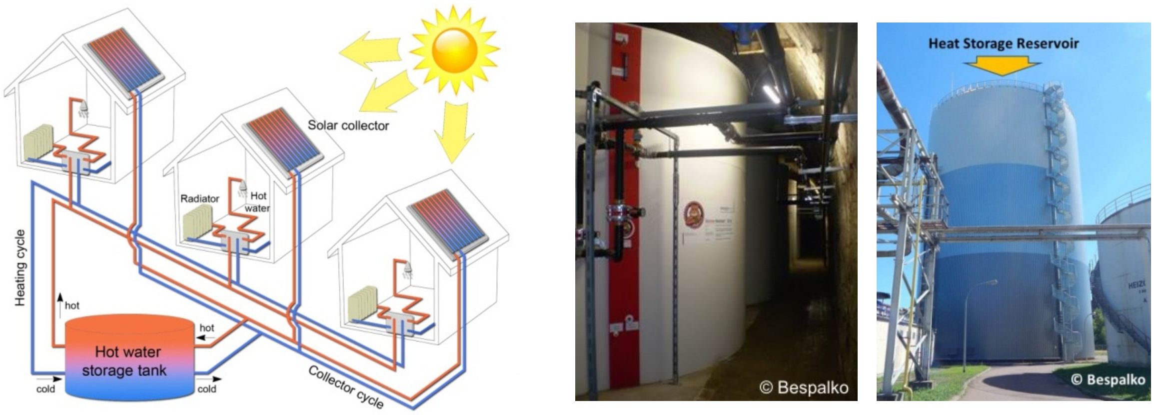
Seasonal heat storage, which is also referred to as the long-term heat storage, is used to accumulate thermal energy, e.g. generated by solar collectors installed on the building roofs (Fig. 7, a), in summer for its further use for heating purposes in winter. Along with the short and medium term heat storage, water (including groundwater) is also the most commonly used conventional heat storage substance to store heat on a seasonal time scale.

Since a bigger size hot water storage tank has the lowest value of the surface to volume ratio, the heat losses through the external walls are much lower. Hence, the seasonal heat storage systems are usually designed as the huge central hot water storage tanks with high storage capacities (Fig. 7 b, c). Moreover, by enlarging the heat storage system size the specific investment costs are reduced drastically. [57]

Generally, for seasonal heat storage, the following technologies are commercially applied: hot water tank, pit also known as gravel-water, borehole, and aquifer TES. Most of them are underground storage systems and therefore hydrogeological conditions of the location chosen for new installation define the use of one or another technology.

Long-term hot water thermal energy storage (HWTES)

Hot water tanks for seasonal heat storage are often made from steel or concrete with/without a stainless steel or plastic liner inside. Along with the advanced heat insulation minimizing the heat losses through the external walls, temperature stratification enhancers are also installed within the tanks to increase the exergy value of the content of the store. Since water has very high value of the specific heat and the power rate for charging and discharging, it is mostly used as a heat storage medium. This type of the seasonal heat storage systems has primarily been implemented in Germany in solar district heating systems with 50% or more of solar fraction [58].



(a) (b) (c)

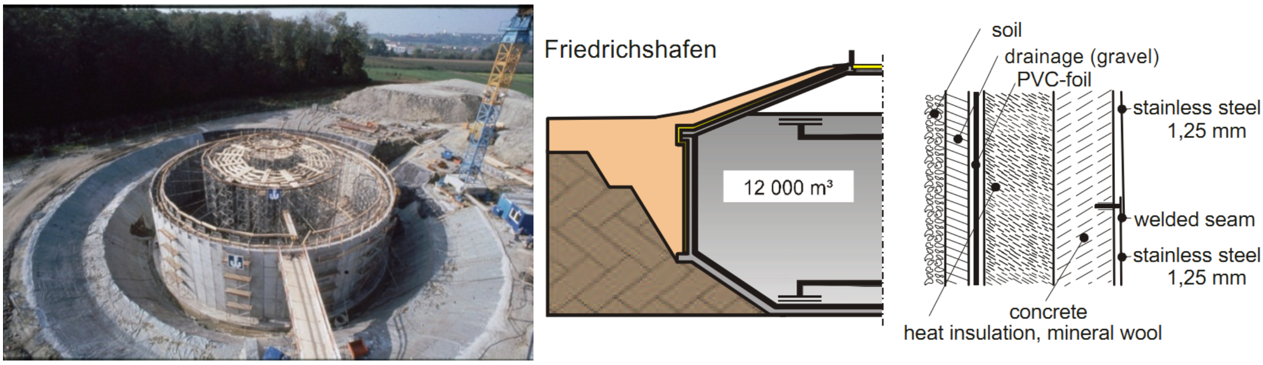
Source: Author's *Source: [59]*

Fig. 7. Solar heating and hot water supply system with central seasonal heat store (left) and examples of the underground and above ground hot water tank installations (right):
(a) functional scheme of the solar community with a central heat storage tank;
(b) 50 m³ heat insulated hot water tanks installed in the basement of the building for long-term solar heat storage (Dessau-Rosslau, Germany);
(c) above ground 20 000 m³ hot water storage reservoir in district heating system (Dessau-Rosslau, Germany).

There are two types of the hot water tanks' installations: above-ground and underground. Above-ground tanks are regular heat insulated tanks, which are installed on the surface of the ground as shown in Fig. 7 (c) or in the basement of the building as it can be seen from Fig. 7 (b). In both examples, the storage capacity of the single tank constitutes 20 000 m^3 and 50 m^3 of the hot water respectively.

In contrast to the above ground installations, the underground concept for constructing the hot water storage tanks benefits from the additional insulation of the external walls by natural soil from the ambient air. Since the subsurface temperature is positive and nearly constant throughout the year, the thermal losses are much lower for this type of the store in winter. The example of the underground HWTES is the hot water storage tank constructed in Friedrichshafen–Wiggenhausen (Germany) to support heating and hot water supply for 570 apartments [60].

Fig. 8 (a, b) illustrates the heat storage reservoir in Friedrichshafen–Wiggenhausen under construction and the internal scheme of the heat storage tank respectively.



(a) *Source: [61]* (b) *Source: [62]*

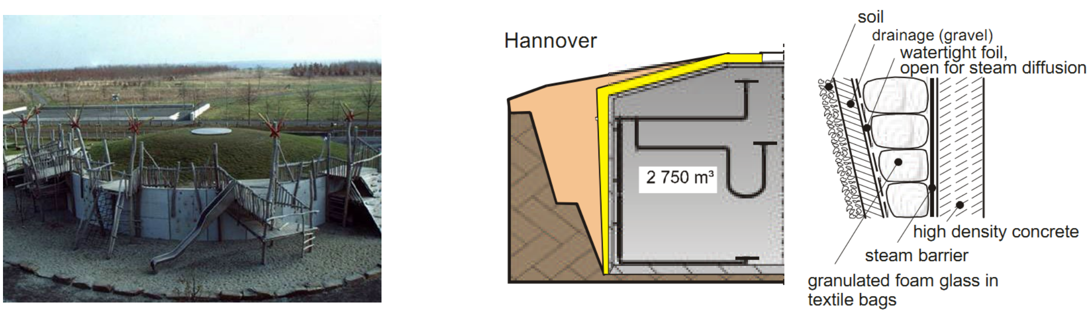
Fig. 8. Heat store in Friedrichshafen–Wiggenhausen (Germany):
(a) construction of the store;
(b) construction of the hot water storage reservoir in Friedrichshafen.

It is obvious that the heat stored in the tanks can only be used without the backing of a heat pump till the storage temperature is higher than the return temperature of the water from the district heating system [63].

The heat storage in Friedrichshafen–Wiggenhausen is in operation since 1996, where the hot water storage tank is partially buried in the ground to keep the heat losses low in winter. The storage was built using reinforced and pre-stressed concrete tank, which is heat insulated only on the roof and at the side walls and lined with 1.2 mm stainless steel sheets inside [60].

However, the cost analysis of the heat storage plant in Friedrichshafen showed that the internal stainless steel liner is a very expensive component of the tank [64]. Therefore, in a new construction concept represented in Hannover-Kronsberg, the liner is avoided by applying high density reinforced concrete [61]. But as high-density concrete is not able to prevent totally the water vapor diffusion through the walls at hot water temperatures, a layer of the vapor barrier is installed between the heat insulation and concrete [65].

Fig. 9 (a, b) illustrates the heat storage reservoir constructed in Hannover-Kronsberg and the internal scheme of the heat storage tank respectively.



(a) *Source: [66]* (b) *Source: [62]*

Fig. 9. Heat store in Hannover-Kronsberg (Germany):
(a) thermal storage tank landscaped as a public area (children's playground);
(b) construction of the hot water storage reservoir in Hannover.

Table 9 represents characteristics of the Friedrichshafen–Wiggenhausen and Hannover-Kronsberg hot water storage plants. In both cases, the planning solar fractions are 47% and 39% of the total heat demand respectively for space heating and domestic hot water preparation. Rest is covered by the fossil energy supply.

Table 9. Characteristics of the hot water storage reservoirs installed in Friedrichshafen–Wiggenhausen and Hannover-Kronsberg (Germany)

Parameter	Friedrichshafen–Wiggenhausen	Hannover-Kronsberg
Solar collector area	5 600 m^2	1 350 m^2
Type of the store	Concrete hot water store with a stainless steel liner inside	Concrete hot water store without internal liner
Volume of the store	12 000 m^3	2 750 m^3
Max. temperature	95 °C	95 °C
Service area	Final stage: 570 apartments in multifamily house	106 apartments in multifamily house
Heated area	39 500 m^2	7 365 m^2
Total heat demand	4 106 MWh/a	694 MWh/a
Solar net energy	1 915 MWh/a	269 MWh/a
Solar fraction (long-term planning)	47%	39%
In operation since	1996	2000

Source: [57, 60, 63]

In the Friedrichshafen-Wiggenhausen storage, a distributed manifold of the vertical stratification enhancer within the tank has only two injectors (Fig. 8, b), located at the top and bottom, for charging and discharging respectively. In contrast, in the Hannover-Kronsberg storage additional injector for charging or discharging was introduced (Fig. 9, b). This injector is placed at one-third of the distance from the top of the storage medium height and provides an optimized flexibility for using different water temperatures at various layers of the stratified hot water storage reservoir. [65]

According to D. Mangold and T. Schmidt [62], the storage capacity of the hot water storage reservoirs is about 60-80 kWh/m^3.

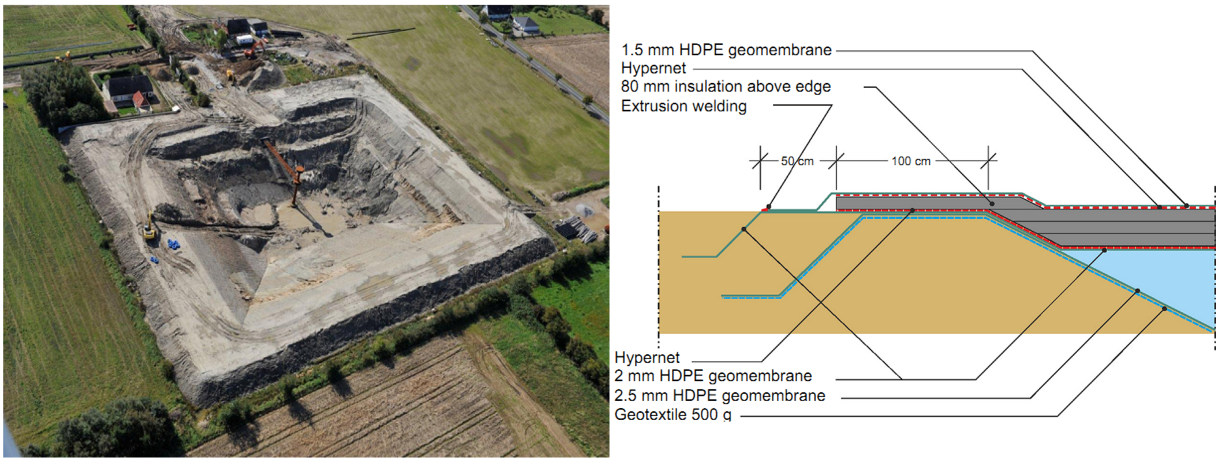
Gravel-water thermal energy storage (GWTES)

Pit thermal energy storage, which is also referred to as a gravel-water, is an underground heat storage technology realized in the form of large basins. In this case, instead of building huge and costly hot water storage tank, an excavated pit with a depth of around 5-15 meters is applied [67]. The pit is typically filled with water as a heat storage medium. Alternatively to water, gravel-water or sand-water mixtures can be used as inexpensive solid fillers with a gravel/sand fraction between 60-70% [67-69]. However, the storage capacity of this type of the storage media is lower than that of water and therefore the storage volume should be by 30-100% larger compared to HWTES technology to store the same heat amount. Nevertheless, as shown in [67], in contrast with the tank heat storage, use of the pit concept allows reducing considerably the specific cost of the store, especially for large-scale projects.

To avoid water leakage through the bottom and sides of the pit, a plastic liner, usually high-density polyethylene (HDPE), is implemented and welded separating the storage medium from the surrounding soil and making the underground storage basin tight. In addition, the pit has heat insulation usually on the sides and top to make heat losses low. Moreover, the heat stratification enhancers are also applied to increase the exergy value of the content of the store as do tank storages. [58]

Extraction and injection of the heat can be realized in an indirect way by means of a heat exchanger embedded in the pit or directly through piping installed at different layers of the store [65]. The pit heat storage operates under no overpressure, and therefore the maximum operating temperature is up to 95 °C only. [70]

The example is the pit heat storage built in New Marstal in southern Denmark with 75 000 m^3 of hot water inside providing approximately 7 500 MWh of solar heat for space heating of buildings with 27% of solar fraction and the lowest specific cost among other projects, which is the largest underground TES project in Europe (Fig. 10).



(a) (b)

Fig. 10. New Marstal pit heat storage with 75,000 m^3 of the hot water (Denmark):
(a) construction of the store;
(b) scheme of the pit heat storage.

Source: [58]

Borehole thermal energy storage (BTES)

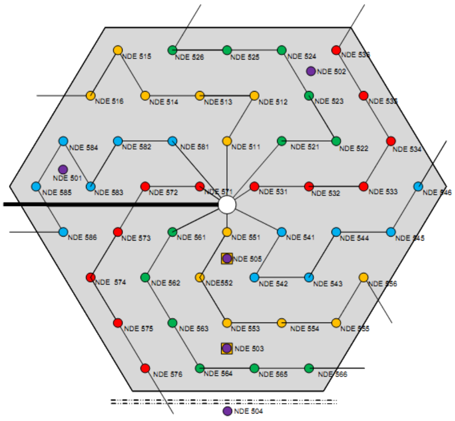
In BTES, soil serves as the heat storage medium. Here, heat is transferred to the soil by means of the ground-coupled heat exchangers installed in a number of the drilled vertical holes with a depth of up to 200 meters [71, 72] and with around 3-4 meter separation from each other [62] as shown in the layout (Fig. 11, a). In this case, the heat exchangers applied are usually in the form of U–shaped or concentric pipes (Fig. 11, b) and made of HDPE to prevent corrosion and consequently increase their lifetime [65]. The vacuous space between the heat exchangers and the surrounding soil is filled with the grouting to be a good thermal conductor between pipes and soil. The pipes of ground-coupled heat exchangers are connected to a central connection well and on the top of the borehole storage, the heat insulation with the ground as a covering layer finalizes the construction (Fig. 11, b) [58]. The thermal capacity of the BTES depends considerably on the water contents in the soil. Therefore, the water-saturated soil is the most suitable for BTES installations. On the other hand, since there is no any heat insulation in the subsurface no natural groundwater flow should be existent in the location where the BTES is planned [62]. The storage capacity of the BTES technology is about 15-30 kWh/m^3 [62].

In summer, the hot HTF is circulated in heat exchangers transferring the surplus heat, from e.g. solar field, to the soil for long-term storage. In winter, the HTF has reverse circulation and transfers the heat stored back to buildings for heating purposes. Water is mostly used as HTF. However, in some cases to prevent possible HTF freezing in winter water-antifreeze mixture is applied.

Fig. 11 (b) illustrates the common types of the ground-coupled heat exchangers and their typical installation scheme.

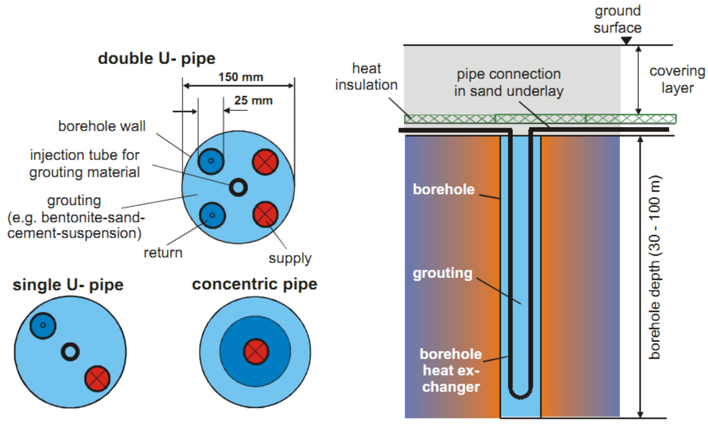
Depending on the working temperature range, BTES can be applied for low-temperature (0-40 °C) and high-temperature (40-80 °C) heat storage in the subsurface [73]. In the first case, extraction of the low-temperature heat occurs in combination with the heat pump. With the high-temperature store, the heat is extracted and delivered to the consumers directly with the HTF circulation. However, since the subsoil storage volume is not insulated soil overheating at high temperature may cause a moisture flow and drying effect of the soil, which will generate soil cracks and obviously reduce the performance of the underground heat store [65].

Many projects are about the storage of solar heat in summer for space heating of houses in winter. Thus, table 10 shows characteristics of some of the borehole application projects for large-scale heat storage in Europe.



(a)

Source: [58]



(b)

Source: [62]

Fig. 11. Borehole TES:
(a) a layout of the drilled boreholes; (b) type of borehole heat exchangers and sample installation.

Table 10. Characteristics of some large BTES projects in Europe

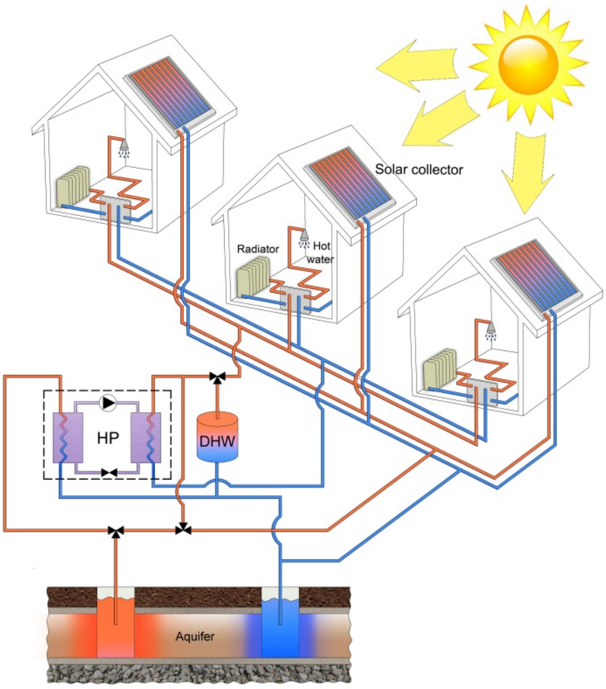
Country	**Plant**	**Year of initial operation**	**Service building**	**Solar collector**	**Borehole storage**	**Load size (MWh/a)**	**Solar fraction (%)**
Italy	Treviglio	1985	Existing residential area	2 727 m^2, roofmounted, flat plate	43 000 m^3	-	70
Sweden	Lidköping	-	New residential area, 40 two family houses	2 500 m^2, roof module	15 000 m^3 clay	980	70
Sweden	Anneberg	2002	50 residential units with about 120 m^2 floor area each	2 400 m^2, roofmounted	60 000 m^3 crystalline rock; 100 65-m-deep boreholes that filled with double U-pipes	550	70 (calculated)
Germany	Neckarsulm	1999	20 000 m^2	5 470 m^2	6 3360 m^3, doubled in U-shape duct of 30-m-deep	1 700	50
Germany	Attenkirchen	2002	6 200m^2, 30 low energy homes	836 m^2	9 350 m^3, 90 borehole double-U-loops heat exchangers with 30 m depth	487	55
Germany	Crailsheim	2007	260 houses, school and gymnasium	7 300 m^2 vacuum tubes collector	37 500 m^3, double U-pipes, 80 boreholes with a depth of 55 m	4 100	50
Netherlands	Groningen	1984	New residential area	2 400 m^2 roof-mounted evacuated	23 000	-	65
Canada	Drake Landing Solar Community (DLCS)	2007	52 detached energy efficient homes	2 293 m^2 flat-plate, roof-mounted	33 657 m^3; 144 boreholes with a depth of 35 m	530	97

Source: [74]

Aquifer thermal energy storage (ATES)

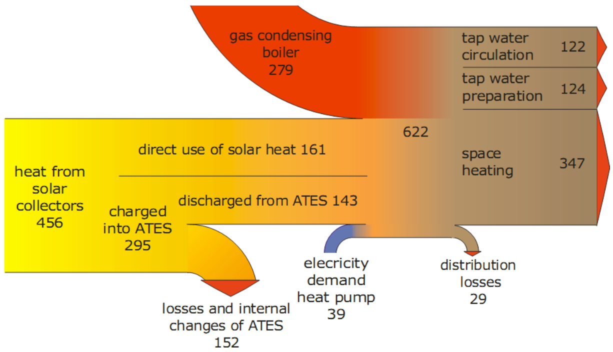
The term "*aquifer*" refers to a permeable and saturated with water underground layer of porous rock or unconsolidated materials such as soil, sand, clay, gravel, loam and etc. [75]. The aquifer can be found in the subsurface where geologic formations are permeable enough to rainwater and able to store large quantities of groundwater [76]. At the same time, the groundwater temperatures stay almost constant at 1-2 °C in the depth between 10 and 30 meters [77] and as a result, in locations where the groundwater is available, the aquifer may serve as a reliable source of low-temperature geothermal energy [76].

An example of the ATES system is a system installed in Rostock-Brinckmanshöhe (Germany) to supply a multifamily house with a heated area of 7 000 m^2 in 108 apartments with space heating and domestic hot water preparation (Fig. 12). According to the heat balance diagram illustrated in Fig. 12 (c), the efficiency of the ATES system constructed in Rostock is closed to 50%.



(a)
Source: Author's

(b)
Source: [78]



(c)
Source: [78]

Fig. 12. Aquifer TES:
(a) functional scheme of the ATES system operation;
(b) multifamily house with ATES system installed in Rostock-Brinckmanshöhe;
(c) energy flow diagram for the year 2003 (numerical values in MWh).

In contrast to the BTES, the ATES is distinguished as an open heat storage system because the groundwater is used both as HTF and heat storage medium.

Injection and recovery of the heat into and from the groundwater is realized by using two or several wells drilled into the aquifer named warm and cold wells. In a charging mode, the groundwater is extracted from the cold well, transported through the heat exchanger where it is heated up directly by utilizing industrial waste heat or solar heat in summer and then is injected back into the aquifer for storage forming so-called a warm well nearby. In a discharging mode, the warm water is extracted from the warm well and recovery of the heat stored occurs by means of a heat pump, and used for space heating or domestic hot water preparation in winter. Due to the changing and discharging flow directions cold and warm wells have to be equipped with pumps, production and injection pipes [78]. Since in the subsurface, there is no any heat insulation between the wells and the surrounding soil the natural groundwater flow should be as low as possible to reduce potential heat losses.

Depending on the temperature level of the heat stored, the ATES systems are classified as: (1) cold storage, (2) heat storage, or (3) combined cold and heat storage systems. [79]

Injection, storage, and extraction of the chilled water in a temperature range between 6-12 °C provide excellent cold storage with high efficiency between 70 and 100 %. This temperature level is appropriate for cooling purposes in summer without the need for a heat pump operation. [76]

Injection, retain and recovery of the heated water allow heat storage in the aquifer. [76] Potentially the temperature of the heated water injected into the subsurface could be up to 95 °C because the groundwater is not heavily pressurized and therefore higher temperatures are impossible to be achieved. At the same time higher temperatures of the heat stored causes high heat losses and as a result efficiency of the heat storage is lower than that for cold storage and varies between 50-80%. Along with this, some countries, such as Germany, have implemented restrictions aimed to protect environment from warming and therefore most of the ATES installations operate at low or moderate temperatures up to 50 °C [63] and therefore heat extraction from the well is realized by heat pump operation to cover heat demand in winter.

Combined ATES systems provide both cold and heat storage. According to Ghaebi et al. [80], the ATES system used both for cooling and heating purposes is the best solution in terms of the high value of COP. Thus, the COP values of about 17.2 and 5 can be achieved for cooling and heating applications respectively.

Table 11 represents characteristics of the ATES system installed in Rostock-Brinckmanshöhe. The planning solar fraction is 62% of the total heat demand including space heating and domestic hot water preparation. The remaining heat load is covered by a gas condensing boiler [78].

Table 11. Characteristics of the aquifer TES system installed in Rostock-Brinckmanshöhe (Germany)

Parameter	Rostock-Brinckmanshöhe
Solar collector area	980 m^2
Type of the main store	aquifer TES
Life time for ATES	40 years
Depth of the aquifer	15-30 meters
Number of the wells drilled	2
Distance between wells	55 meters
Max. design ground water flow rate	15 m^3/h
Hydraulic conductivity of the aquifer	k_f=6·10^{-5}-9·10^{-5} m/s
Mean volumetric heat capacity	$2.7\,\frac{MJ}{m^3 \cdot K}$
Mean thermal conductivity	$3.2\,\frac{W}{m \cdot K}$
Volume of the ATES	20 000 m^3
Max. heat storage temperature	50 °C
Type of the buffer heat store	Insulated hot water tank
Volume of the buffer heat store	30 m^3
Max. temperature of water in the buffer heat store	50 °C
Domestic hot water system	2 central 750-liter tanks
Temperature level used for domestic hot water preparation	65 °C
Type of the heat pump installed	Absorption heat pump
COP of the heat pump	6-7 at the beginning of the discharging period 3.5 at the end of the discharging period
Heat output of the heat pump	100 kW_{th} (thermal power)
Service area	108 apartments in multifamily house
Heated area	7 000 m^2
Total heat demand	497 MWh/a
Solar net energy	307 MWh/a
Solar fraction (long-term planning)	62%
In operation since	2000

Source: [57, 60, 63, 78]

Comparison of the underground TES technologies is presented in Table 12.

Table 12. Comparison of the different seasonal heat storage technologies

Type of the underground TES	HWTES	GWTES	BTES	ATES	Source
Storage medium	Water	Water / Gravel-water	Ground material	Saturated water ground	[62]
Heat capacity, kWh/m^3	60–80	60-80 / 30–50	15–30	30–40	[62]
Storage volume (for 1 m^3 of water equivalent), m^3	1	1.3–2	3–5	2–3	[62]
Operational temperature	up to 95 °C	up to 95 °C	0-40 °C (low temperature applications), 40-80 °C (HT applications)	6-12 °C (cold storage), 13-25 °C (low temperature heat storage), 25-40 °C (moderate temperature heat storage), 40-95 °C (HT heat storage)	[57, 60, 63, 65, 79, 81]
Efficiency	90%	90%	40-60%	70-100% (for cold storage), 50-90% (for heat storage)	[63, 65, 67, 73, 79]
Approximate cost per 1 m^3 of water equivalent * **	160 Euro/m^3	120 Euro/m^3	95 Euro/m^3	40 Euro/m^3	Estimated based on data from [67]
Advantages	- High thermal storage capacity of water, - High charging/discharging power, - Freedom of design (geometry), - Thermal stratification	- Reasonable construction cost, - Medium (for gravel-water mixture) to high (for water) thermal storage capacity, - Nearly unlimited dimensions of the store, - Thermal stratification	- Low construction cost, - Easily extendable just by drilling additional boreholes	- Very low construction cost, - Medium thermal storage capacity	[82]

Table 12. Comparison of the different seasonal heat storage technologies (continued)

Type of the underground TES	HWTES	GWTES	BTES	ATES	Source
Disadvantages	- Limited size (<100 000 m³), - High construction cost	- Sophisticated construction of cover (so called floating cover for water), - Limited freedom of design (especially slope angle of the sides)	- Low thermal capacity, - Low charging/discharging power, - Buffer storage required, - Heat pump recommended, - Limited choice of locations - No thermal insulation at sides and bottom	- Low/medium charging/discharging power, - Heat pump recommended, - Very limited choice of installation, - No thermal insulation	[82]
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 (k_f<10^{-10} m/s), - Natural ground-water flow <1 m/a, - 30–100 m deep	- Natural aquifer layer with high hydraulic conductivity (k_f>10^{-5} m/s), - Confining layers on top and below, - No or low natural groundwater flow, - Suitable water chemistry at high temperatures, - Aquifer thickness 20–50 m	[62]

* The cost does not include VAT, system cost (e.g. cost of the heat pump if necessary), and maintenance cost.
** The cost was estimated for four reference pilot projects: München (HWTES), Chemnitz (GWTES), Neckarsulm (BTES), and Rostock (ATES).

Source: Author's

The cost estimation of the four different underground TES technologies described, clearly shows that the most expensive way to store heat on a seasonal time scale is HWTES. At the same time, ATES seems to be the most inexpensive technologies among others. The cost was estimated using data from [67] for four reference projects with approximately the same amount of water equivalent storage volume. Generally, as shown in [67], there is a strong tendency in the reduction of the investment cost from 250 Euro to 40 Euro per 1 m^3 of water equivalent with increasing the storage volume.

Summary and conclusions

The scope of this paper was to give an overview of the existing sensible heat storage technologies applied in thermal energy systems based on fluctuating renewable heat sources to overcome the problem of mismatch between the thermal energy supply and consumption.

In the analysis, the general classification and thermodynamics of the heat storage methods were presented and the following sensible heat storage technologies were discussed: hot water storage with thermal stratification, HT heat storage in CSTP plants, and seasonal underground TES technologies, especially: HWTES, GWTES, BTES, and ATES.

Many factors influence the selection of the appropriate heat storage method. First of all, the time scale to store heat, temperature level needed, and estimated heat demand.

If operation temperature is below 100 °C, storage period is short- or medium-term, and the heat demand is only for a single family house then the conventional hot water storage tank is the most suitable technology because it offers the most inexpensive way to store heat. Therefore, this type of technology dominates in the heat storage market. Moreover, hot water tank always benefits from initiation of the temperature stratification within the storage reservoir since the exergy value of the store as well as the solar collector's efficiency increase with enhancing the temperature stratification.

When it comes to implementing the long-term heat storage or heat storage for multifamily houses/solar communities with high heat demand, one of the four underground heat storage technologies, notably: HWTES, GWTES, BTES or ATES, can be employed. Here, the geological conditions of the place chosen for underground installation play a significant role. At the same time, as shown in our analysis, among underground heat storage technologies, ATES is the most inexpensive and relatively efficient way to store heat. However, since the heat is stored at low or moderate temperature level, the heat extraction is impossible without the heat pump operation.

Concerning HT heat storage, crucial for CSTP plants, currently, molten salts are largely used for this purpose in 2-tank direct and indirect schemes. However, these two HT heat storage concepts require huge storage volume because the specific heat of the molten salts is relatively low.

The storage substances applied for sensible heat storage have the following advantages:

- they are low priced, e.g. water, molten salts etc.,
- they are durable since there is no any chemical decomposition during operation and they offer long-term exploitation without performance degradation,
- they are relatively simple in use in terms of realization of the heat and mass transfer, e.g. conventional heat exchangers and pumps can be utilized for transferring heat and conveying the HTF or even storage media (e.g. water or molten salts) respectively.

On the other hand, sensible storage substances have some inherent imperfections:

- only small heat amount can be accumulated compared to other storage technologies such as latent, sorption and thermochemical heat storage, therefore the sensible heat stores should contain a large volume of the storage medium to retain the same heat amount,
- sensible storage substances cannot provide constant temperatures in charging and discharging and therefore to store more heat greater overheat is needed, which results in essential heat losses and reduction of the storage efficiency.

Thus, in the recent years, the results achieved in developing TES systems show that the sensible heat storage technologies are the most technically reliable and economically feasible. As a consequence, nowadays the sensible TES systems are the most applicable storage systems in tandem with the intermittent renewable heat sources. Nevertheless, research is still needed, especially on material and the system design, for the purpose to reduce cost, increase the storage capacity and efficiency.

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