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REPORT ON STORAGE MATERIALS AND SYSTEMS

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D2.1 Report on storage materials and systems

1. Introduction

Thermal energy storage (TES) is defined as the temporary holding of hot or cold thermal energy for later utilization. TES is an essential component in systems in which the energy production does not fit the energy demand. Therefore, it is strongly recommended to add TES storage in systems involving renewable energy sources or waste energy in order to increase energy optimization.

Different materials and technologies are used to store thermal energy from solar energy. Technologies are classified as sensible, latent and thermochemical heat storage. Nowadays, the most used technology and material is sensible storage in water tanks, due to its low cost and its appropriate thermal properties. Nevertheless, ground and aquifer storage are often being implemented.

The selection of a TES system for a particular application depends on many factors, including storage duration, economics, supply and utilization temperature requirements, storage capacity, heat losses and available space.

The objective of this deliverable is to gather and summarize, for each technology, all the information about the technical properties, environmental impacts, prices, Life Cycle Costing (LCC), market level and other important parameters.

The collected information is to be used in the decision of the more adapted technology for different possible thermal project requirements and locations.

The technical and economic information for all the technologies is used in next deliverables.

This project could be considered as a continuity of the Einstein Project, Chess Setup goes deeper towards materials properties, range of applications, constraints and operating parameters. Additionally, apart from the sensible heat storage systems covered in Einstein, Chess Setup analysed phase-change materials, as a way of latent heat storage, and thermochemical materials which can store and release heat during endothermic/exothermic *processes.*

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2. Main parameters for TES system selection

There are multiple parameters that have to be analysed before choosing the appropriate material, system and volume for solar thermal energy storage systems.

In the following section, the main parameters that have to be considered for the selection of a Thermal Energy Storage (TES) system are analysed:

- Storage Temperature
- Temperature requirements for heating systems
- Thermal storage capacity
- Thermal power
- Storage duration
- Efficiency
- Location
- Cost

2.1. Stored Temperature

One of the most important parameters of a TES system is the storage temperature. Storage temperature should be considered to define material, volume, shape, insulation, charging and discharging as well as auxiliary installations.

Temperature should be stored in quality conditions in order to maximize the use of the energy. The term that is used to measure the quality of the energy is exergy.

Exergy is defined as the maximum amount of work that can be obtained when the system moves from a particular state to a state of equilibrium with the surroundings.

In the particular case of TES, for the same amount of energy stored, a system with higher temperatures of storage has a higher exergy than a system with lower temperatures of storage.

In this section temperature production of different energy sources are described, as well as, stratification, the distribution of temperatures in TES that increases exergy.

2.1.1. Source of Thermal Energy Production

There exists a large variety of thermal energy production types such as boilers, ovens, incinerators or electric water heaters. They may use multiple sources of energy (natural gas, fuel-oil, electricity, biomass, waste...) using as transport medium water, saturated water, steam, thermal oil ... at multiple temperatures.

Most of the conventional thermal energy productions are not commonly used as a source of thermal energy production for large TES, due to their good and economic regulation systems and installations to match thermal production and demand.

This section will be focused on thermal energy sources that are commonly used for TES.

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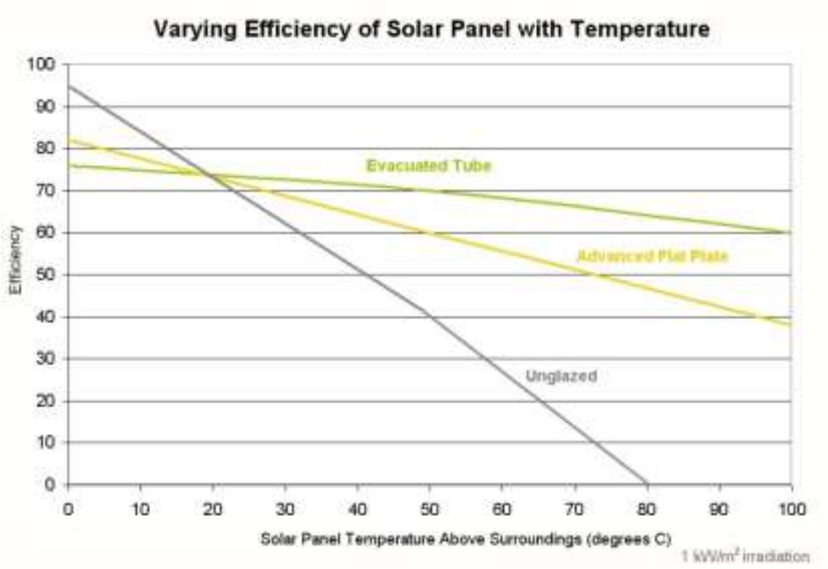
2.1.1.1. Solar Thermal Panels

In thermal panels, thermal performance may be as high as 90%. Performance drops with higher differences between outdoor temperature and panel water temperature. As it may be seen in the graph bellow, the type of solar thermal panel has an impact in thermal performance:



Graphic: Thermal performance for different types of solar thermal panel (Source: Vidrian Solar)

In conventional thermal panels output temperatures may range from very low temperatures, 30-40 ºC, up to 150ºC.

State of the art of thermal panels is analysed in more detail in Work Package 3.

2.1.1.2. Photovoltaic Thermal Panels

Photovoltaic-Thermal (PVT) panels, also called hybrid panels, produce electricity and thermal energy directly from solar radiation. They have a thermal performance at around 50% of energy radiation input when working with small differences between water temperature and PVT water temperature. On the other hand, with big differences between outdoor temperature and PVT water temperature, thermal performance drops notably.

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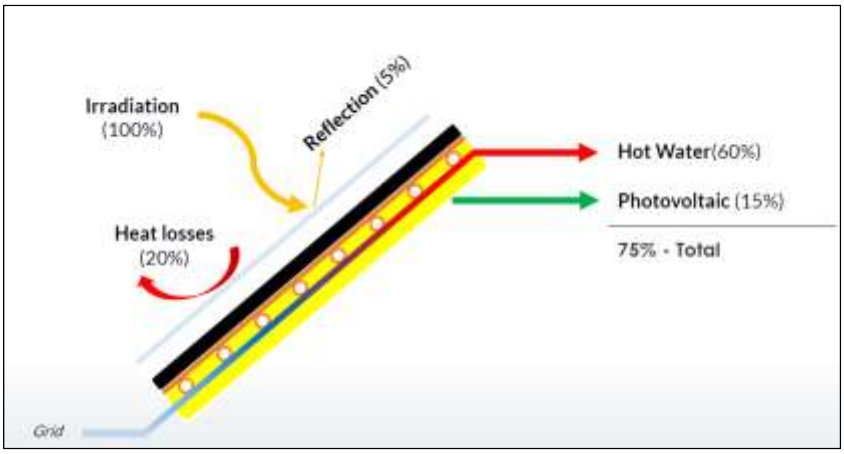
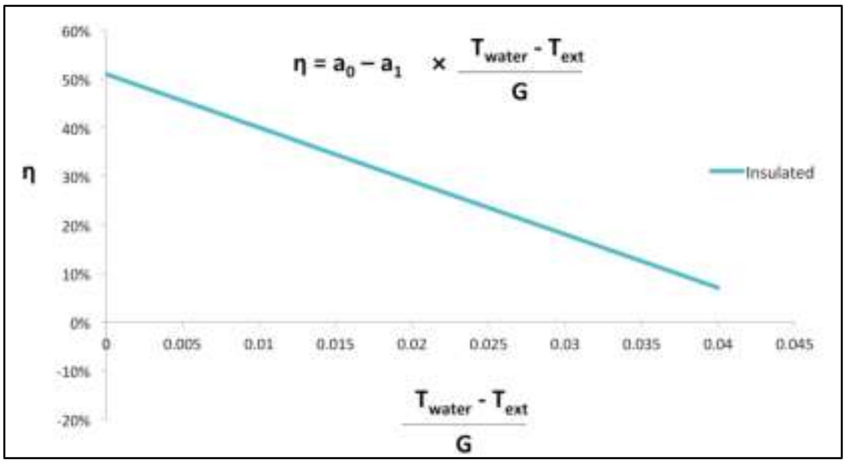


Figure: PVT production of hot water, electricity and thermal losses (source: Abora)



Graphic: Dual Sun Wave performance for insulated PVT panels for temperature difference (Source Dual Sun Wave)

Output temperature in PVT panels for storage may be recovered from very low temperatures up to 75ºC or even 135ºC depending on the type of panel and efficiency desired.

For an optimized PVT and STES system, an output temperature of PVT panels from 30ºC to 70ºC is considered.

For regions with temperatures under 0ºC, in order to prevent freezing risk, PVT water should be mixed with antifreeze such as propylene glycol or ethylene glycol. A Heat Exchanger should then have to be installed between the storage water and the PVT panel. This glycol must not be allowed to overheat in summer otherwise the system will potentially fail.

Special designed heat exchangers should be installed to reduce the difference between input PVT water temperature and outlet storage water temperature. Usual heat exchangers in low exergy systems are designed with a temperature difference of 3ºC to 5ºC.

State of the art of PVT panels is analysed in more detail in Work Package 3.

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2.1.1.3. Design solutions to avoid boiling point in storage

Generally spoken, in systems where solar energy delivers heat to a storage vessel, a difference can arise between the solar offer and the heat demand. Boiling danger in the storage vessel can arise if the solar offer exceeds the heat demand by a wide margin. The boiling protection of the storage vessel has three variants: avoidance of too strong heating, heat absorption by a cooling mass, or heat draining by circulation (including using a colder water layer on the bottom in case of water temperature stratification).

In case that the solar collector is controlling the boiling situation, everything depends on the collector type, such as flat plate, vacuum tube, or PVT. For instance, if the collector is high temperature resistant (vacuum tube), the circulation can be stopped, to protect the system, and its tube connections with the collector. A well-known alternative is water draining, and refilling the collector (flat plate).

Swimming pools are a very common application for thermal panels and PVT as a mass to be heated, as a well as a mean of heat dissipation, because there exist different configurations to cover thermal demand to avoid panel overheating as shown in the figure below. For instance, the advantage in case of a sports centre with swimming pools heat demand, if there is an overheating episode in the tank, heat could be directly delivered to auxiliary swimming pools.

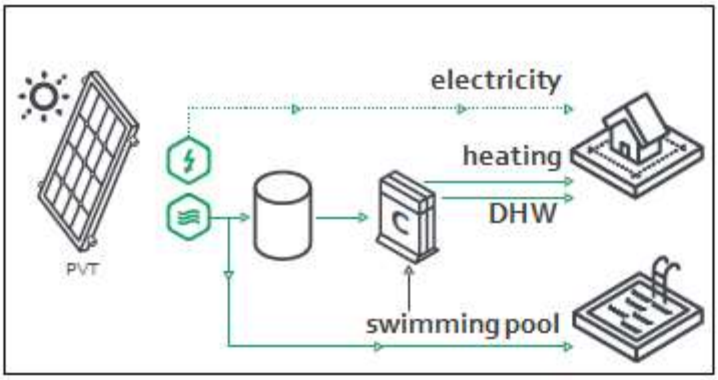

Figure: Possible system configurations PVT (source: Abora)

2.1.1.4. Combined Heat and Power Plants

In combined heat and power (CHP) plants, electricity and useful heat are produced at the same time.

Engines and turbines are the most common CHP power plants. The primary source of energy is usually gas, fuel, coal, biogas or biomass.

In engines, useful heat is recovered in intercoolers, cylinder sleeves, oil cooling and exhausts gases. In conventional CHP engine systems, energy is recovered in water mainly at 90ºC of temperature with a small portion of energy at around 40ºC.

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On the other hand, in turbines useful heat is recovered in exhaust gases with a very high temperature. Energy is recovered in steam, water or superheated water, usually with temperatures higher than 100ºC.

2.1.1.5. Industrial Waste Heat

There is a huge diversity of industrial processes that may produce recoverable waste heat. Temperatures ranges of waste heat may go from as low as 20ºC-30ºC to temperatures higher than 500ºC in foundry plants.

2.1.1.6. Heat Pump for electricity optimisation

Heat pumps working with electricity may also be a source of thermal energy production. They are used in different cases, in order to:

- Maximize off-peak electricity
- Increase the use of renewable electricity in peak production
- Balance thermal energy between day and night

Heat pumps work with a cold source (water or air) and a hot source (water or air). Heat is taken from the cold source and dissipated in the hot source. Heat pumps performance decreases with higher temperature gaps between the cold and hot sources.

Air to Water heat pumps as well as Water to Water heat pumps, have a temperature production in conventional systems that ranges from 30ºC to 60ºC. FP7 EINSTEIN developed heat pumps appropriate for STES operation.

2.1.1.7. Review of thermal energy production

Source of Energy	Output Temperatures
Photovoltaic thermal panels	20ºC-135ºC
Solar thermal panels	20ºC-150ºC
CHP Engines	40ºC-90ºC
CHP Turbines	70ºC-180ºC
Industrial waste heat	20ºC-500ºC
Heat pump for electricity optimisation	30-60ºC

Table: Energy production Output temperatures (Source: Veolia and Einstein Project)

2.1.2. Thermal Stratification

Thermal Stratification is the formation of layers of decreasing density by height that is caused by the effect of temperature on density.

Exergy improvement in TES storage is achieved by thermal stratification; that is, having a higher temperature than the overall mixing temperature that can be extracted at the

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top of the storage and having a lower temperature than the mixing temperature that can be drawn off from the bottom.

Stratification also increases the efficiency of energy production systems, such as thermal and PVT panels.

Stratification is difficult due to agitation and mixing. There is a certain amount of diffusion from the entering fluid (to the stored fluid) before it reaches the appropriate density level. A part from good thermal stratification by reducing mixing, it is equally important to maintain the temperature layers. There are heat losses in the surface of the storage walls, the temperature of the fluid near the vertical walls is lower, leading to natural convection currents that destroy the temperature layers. In order to maintain stratification over long time intervals, the tank should be provided with extremely good thermal insulation or with special installations.

Sensible Heat Storage (SHS), using water as a base of storage, may be designed to have stratification.

2.2. Temperature requirements for heating systems

In order to ensure the highest possible exergy of the system, the temperature and profile requirements of secondary installations should be previously analysed.

Modifications in secondary installations should be encouraged before choosing the final TES solution.

In this section "District Heating Networks" will be described separately from the description of thermal uses in Buildings.

2.2.1. District heating network

District heating networks are systems that are based in a centralized production and a distribution heat for residential and mixed-use developments.

The primary district heating network typically transports the heated water from the central boiler house to a substation located next to the customer residence. From this substation, the heat is then supplied to the customer and used, for example, to heat radiators or provide domestic hot water (DHW).

District Heating Networks are located mainly in Northern and Eastern European countries. Ideal locations for District Heating Networks are countries with a high heating demand with dense populated areas.

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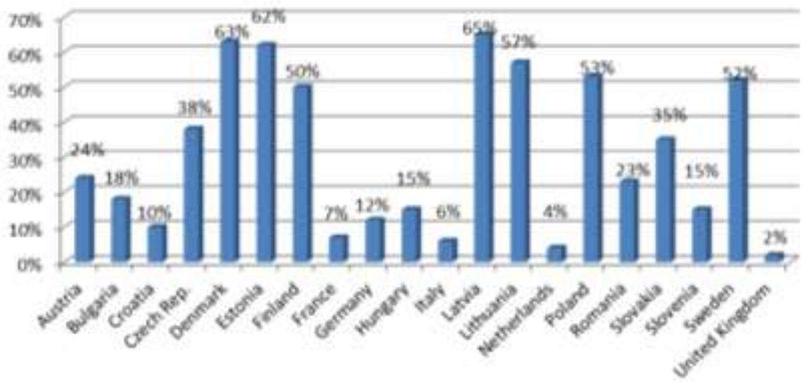

Chart: Percentage of citizens served by District Heating (Source: Euroheat)

District heating networks may be designed to transport water in different forms:

- Hot Water: They are the most used in residential heating networks
- Superheated water (pressured water above 105ºC)
- Steam

District heating networks usually have an operating supply temperature of 70-90ºC, with a designed temperature return of 60 to 70ºC.

Distributed solar network configuration

Previously, in the Einstein Project, it was analysed a solar district heating network with STES support, that had a distributed configuration of auxiliary systems.

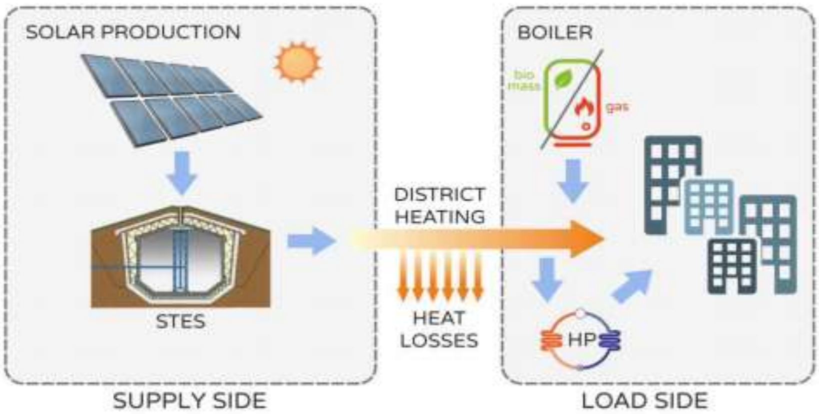

Figure: Solar District Heating (Source: Einstein project)

Currently, low temperature district heating networks are being designed to operate in the range between 50-55°C to 60-70 °C for supply temperatures and 25-30°C to 40°C for return temperatures.

That system could provide thermal energy to High Temperature (HT) and Low Temperature (LT) customers.

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The supply temperature of the district heating network depends on the maximum temperature available inside the STES. It is estimated that solar district heating networks should work between 30ºC to 70ºC of supply temperature.

This system has big advantages such as:

- Reduce heat losses
- Increase exergy
- Increase thermal/PVT panel performance
- Adapt to each customer
- Benefit and encourage low temperature customers

2.2.2. Thermal uses in Buildings

The biggest thermal uses and demands in residential, office and hospital buildings is heating and Domestic Hot Water (DHW). There are a large variety of installations and sources that supply the required energy.

Another common use that requires a big quantity of energy is heated pools. They have a more stable heating demand are used throughout all European countries.

2.2.2.1. Heating needs

Heating in buildings is the largest demand in almost all European Regions. They may be analysed and forecasted. They depend on:

- Heated Volume
- Contact Surfaces
- Indoor Temperature
- Outdoor Temperature
- Occupation
- Radiation
- Air leakage
- Insulation

Heating Degree Days (HDD) is often used to measure heating demand in a particular location. HDD are calculated with outdoor temperature s and common indoor temperature.

The main distribution system used for heating is water. In conventional systems, water is heated in a centralized production (boiler, air/water pump, heat exchanger …), then distributed by a circulator pump in a closed water system, to the final indoor heating devices.

The flow and return temperatures required in the distributed water system depends mainly on:

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- Indoor heating equipment
- Outdoor temperature
- Building design characteristics
- Indoor desired temperature

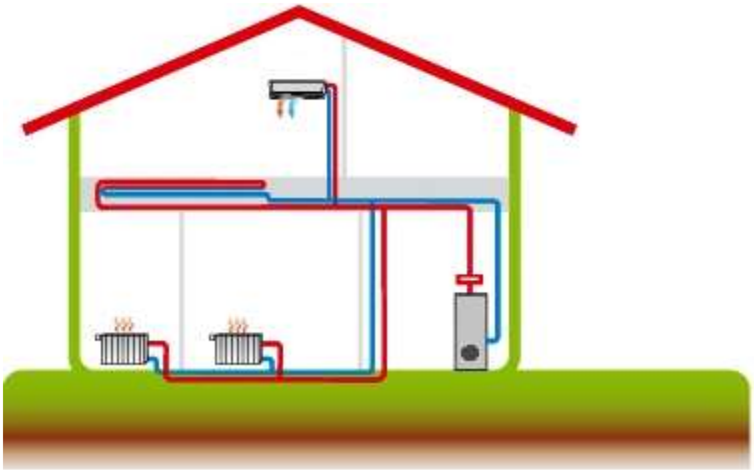

Figure: Heating water distribution system (Source: Delta Techniki)

Indoor heating devices are the key design element in a heating system. They have to be designed to be able to ensure comfort temperatures while working in extreme outdoor temperatures.

Different heating equipment is available in the market:

- Radiator: Conventional radiators are the traditional heating devices. They were typically designed to work with a flow temperature up to 80ºC, heating rooms through radiation and air convection. Modern systems are designed with radiators for low temperatures. These radiators are physically and technically the same but with a bigger size. Low temperatures radiators, are usually designed to work with temperatures lower than 55ºC.
- Underfloor heating/Ceiling heating: It is a heating system integrated completely integrated in the building. Working temperatures for heating are very low. Due to the heating transfer area, they may work with temperature lower than 30ºC in flow temperatures. Usual heating temperatures of working are under 40ºC.
- Fan coil unit (FCU): FCU are simple heating devices. They are made up of a fan that blows air through a coil filled with circulating heating water. They may be designed for different flow temperatures, even though the most usual design flow temperature are under 60ºC.
- Air handling unit (AHU): AHU are devices that are used to supply air in specific conditions (temperature, humidity, filtration…). They are usually equipped with heating water coils. The units may be designed for different flow temperatures, even though the most usual design flow temperature is around 50ºC. It may go up to temperatures of 80ºC.

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A control and regulation system may be implemented in all water heating systems in order to adapt water heating temperature to outdoor temperature. The regulation aim is to optimize production performance and thermal losses. Water temperature, although usually adapted only to outdoor temperature, may also be regulated by occupation and schedule.

2.2.2.2. Domestic Hot Water (DHW)

Domestic hot water is drinkable water that has been heated. It may be used for showers, baths and cleaning uses. In buildings, there is usually a separate centralized hot water circuit.

DHW heating needs, for the same volume and temperature, are different through the year and depending on the location. It is due to the cold water inlet temperature variation (See Appendix 1). Cold water inlet temperature depends on location and season.

Two main types of production exist:

- Storage: Drinkable water is heated by an external boiler, solar production, or internal electrical resistance. Water is kept with a temperature over 60ºC (See: Legionella pneumophila), then distributed to all elements of the circuit.
- Instantaneous: Drinkable water is heated directly in boilers with flame or exhaust gases, and electrical resistances. High power production is necessary. In these systems, there are no special temperature requirements. Running cold water is heated up to temperature needs.

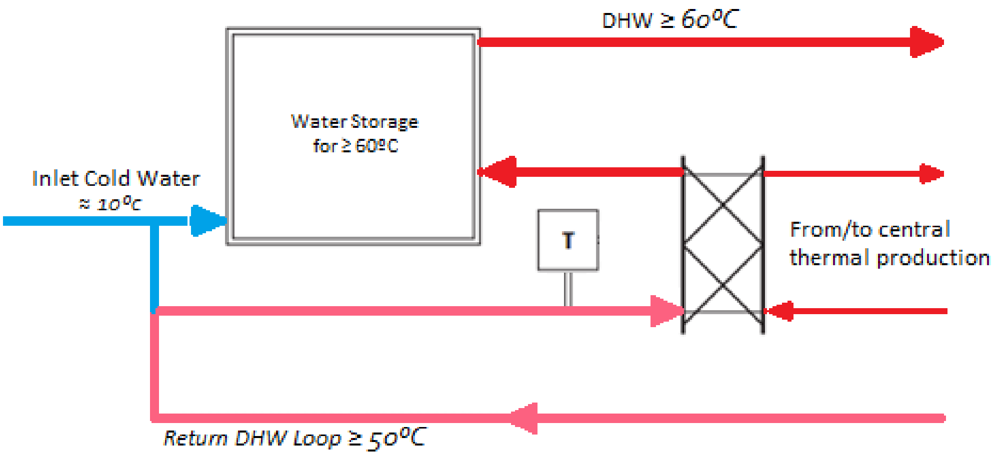

Figure: DHW storage production

Due to the existence of Legionella (see: *Legionella pneumophila*), national norms have had to be adapted. In DHW case, it implies that final hot water tanks and flow temperature have to be controlled above 60ºC. Furthermore, in loop circuits DHW, it

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has to be guaranteed a temperature above 50ºC in every point of the circuit, including return temperatures.

Legionella pneumophila

Legionella pneumophila is a bacteria that can be found in water, and spreads to humans through mist and breathing. It may cause a lung infection or pneumonia and Pontiac Fever. In severe cases, pneumonia infection may cause mortality.

One of the main characteristics of Legionella, is that is a bacteria that live in a wide range of physic-chemical conditions, it multiplies in hot water from 20ºC to 45ºC, being destroyed above 70ºC.

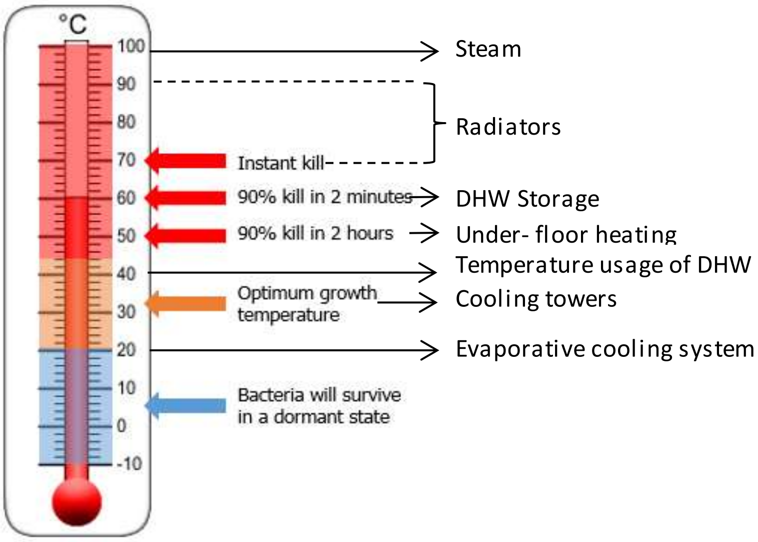

Figure: Legionella Pneumophila growth as a function of temperature

2.2.2.3. Heated pools

Indoor heated pools are very suitable for low exergy system. Heated pools have energy demands of low temperature throughout the year.

Temperatures of Indoor heated pools have to be kept from 24ºC to 30ºC

In accordance with the metabolic activity of the swimmers, the temperature of the heated pool should vary:

- Sports, competition and training: 24ºC-25ºC
- Splashing, recreation and teaching: 26ºC-27ºC
- Private and multi-use: 26ºC-27ºC

Additionally, air conditions of the heated pool hall should be controlled to reduce energy consumption and ensure swimmers comfort. Air temperature is usually kept 2ºC to 3ºC higher than water temperature for energy consumption, while relative humidity is kept below 60-65% for health reasons. Dehumidifiers provided with heating water coils are the most common equipment to control air conditions.

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There are other specific cases, like health care centres and Spa that may have temperatures as high as 42ºC.

Approximately, 4% of the Water Volume is renewed daily, due to the amount of water pollutants that are produced by combination of water chemical components with air and swimmers. Cold water inlet temperature should have to be heated to useful temperature. In Appendix 1, there is a summary of different temperatures of cold water networks for Spain and United Kingdom (UK).

Heated pool's water has specific treatment. It has a closed system recirculation, with inputs of treated water. Heat exchangers are usually the equipment used to transfer the heat between the primary heating system to the Heated Pool water.

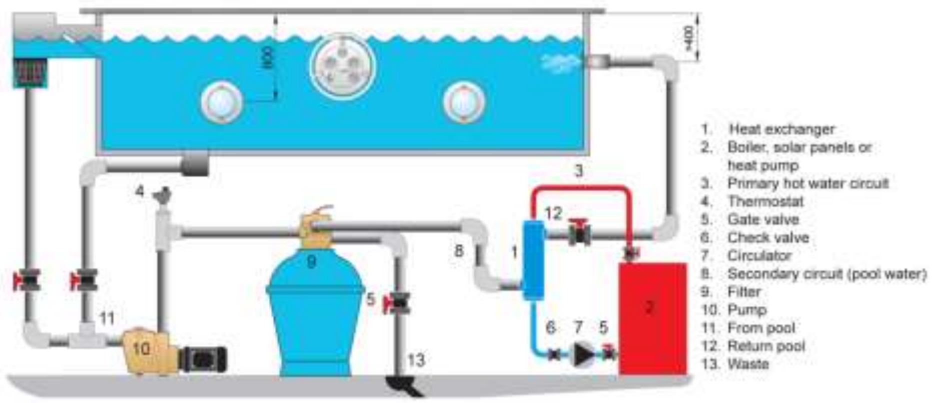

Figure: Typical heating system for heated pools. (Source: http://www.waterware.co.nz/)

The quantity of energy that is needed for heated pools depend mainly of different parameters:

- Energy losses through heated pool walls
- Water evaporation
- Cold water input
- Energy losses through heated pool hall walls
- Controlled or non-controlled air input
- Solar irradiation

2.2.3. Review of temperatures requirements

In the following chart, are shown input temperatures for different applications and systems as an overview.

Type of district heating network	Supply Temperature
Conventional hot water	60ºC-80ºC
Low temperature hot water	50ºC-70ºC
Superheated water	105ºC-150ºC
Steam	130ºC-180ºC
Solar	30-70ºC

Table: Type of DH Networks (Source: Veolia and Einstein Project).

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Uses	Type of equipment	Usual Input Temperatures
Domestic Hot Water (DHW)		≥ 60ºC
Heating Water	Conventional Radiators	50ºC-80ºC
	Low Temperature Radiators	20ºC-55ºC
	Underfloor heating/Ceiling heating	20ºC-40ºC
	Fan coil unit (FCU)	30ºC-60ºC
	Air handling unit (AHU)	30ºC-80ºC
Heated pools	Swimming Pool	24ºC-30ºC
	Health and Spa	24ºC -42ºC

Table: Heating temperatures (Source: Fenercom and Veolia).

2.3. Thermal storage capacity

Thermal storage capacity is a measurable thermodynamic quantity that represents the amount of heat stored that can be used later. In storage research materials, thermal capacity is measured mainly in kWh/t or in kWh/m^3.

For the three existing storage systems technologies, thermal storage capacity is related as follows:

- In **sensible heat storage systems**, "heat capacity" parameter is used which correlates storage capacity variation and temperature, since sensible heat systems changes storage capacity proportionally to temperature. The SI unit for "heat capacity" is J/(K*g), whereas the most used unit is kWh/(kg.ºC) or kWh/(m^3.ºC)

- In **latent heat storage systems** heat is stored or released during a constant-temperature process. Latent heat storage systems work in completely reversible transitions. Latent heat storage systems can be in solid–solid, solid–liquid or liquid– gas transitions. The proportion of the change in the material defines the amount of energy stored.

- In **thermochemical materials (TCM)** systems, heat is stored or released during reversible physical and chemical processes or reactions. TCM includes absorption, adsorption and chemical reactions. At least two substances are needed for TCM process.

Available space for storage as well as price per volume should be essential for choosing the more adapted TES system.

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2.4. Storage Duration

This parameter defines how long the energy charged in TES is stored before being used in the discharging period. Storage duration is one of the main parameters to select TES system. This parameter is highly related with thermal storage capacity.

In solar thermal energy systems, solar irradiation and heat demand have a lag in time for several months. The storage duration in TES for maximum solar heat use, should be designed for seasonal storage. The term used to describe this storage system is Seasonal Thermal Energy Storage (STES).

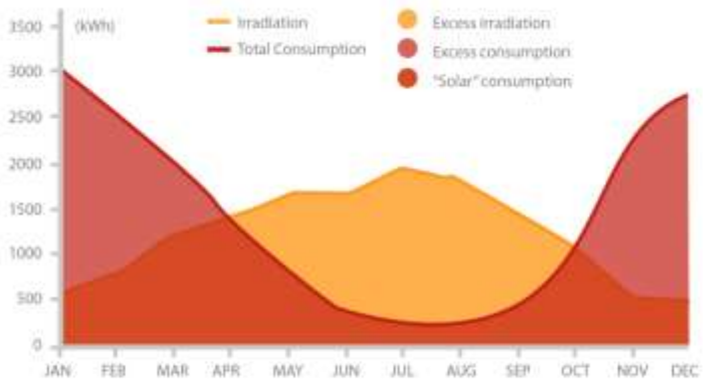

Chart: Annual solar Irradiation and heating demand (Source: Comtes Storage project)

Moreover, in thermal solar storage when a heating pump is needed for thermal use, buffer storage should be used.

In variable tariffs, electricity prices may change notably daily and weekly. The buffer storage for heating pump may be designed to consume electricity for heating storage at the cheapest price, and then release stored heat when needed. The buffer storage and control system should forecast demand and prices.

2.5. Thermal Power

Thermal power in TES systems could be defined as the speed of a system for thermal energy transfer in charging and discharging modes. Heat transfer has three fundamental ways of transferring energy: radiation, conductivity and convection.

Conductivity and **convection** are the most important ways of transferring energy from/to thermal energy storage systems. In liquids, heat transfer is mostly done by convection whereas in solids forms conductivity is the highest form of transferring energy.

Convection transfer capacity varies with viscosity, enthalpy and density parameters of the liquid.

Conductivity heat transfer depends on material conductivity and temperature difference. Materials conductivity is generally represented by W (m.K).

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In TES systems, power extraction should be calculated for every situation. Project's TES design should easily control and forecast maximum power thermal charging. Control systems can be implemented to reduce peak demand by increasing inlet temperature or by anticipating secondary needs.

Power thermal discharging is usually higher and less predictable than thermal charging. A specific analysis should be made considering the secondary installation profile demand. Schedules, person's behaviour, outside temperature and water temperature needs of every secondary installation are parameters for the analysis. Using back-up installation, buffer tanks as well anticipating solar production and secondary needs may reduce peak thermal power discharging demand.

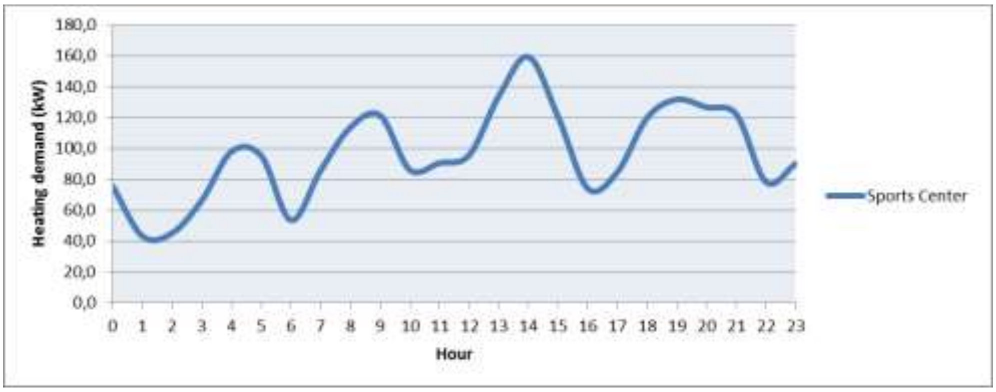

Chart: Swimming-pool and DHW January demand in Barcelona (Source: Veolia)

2.6. Efficiency

Efficiency of TES systems are defined as the ratio between the thermal energy used in charging the TES and the energy delivered to users after the storage period. It is often indicated as a percentage.

Thermal energy losses in charging, discharging and storage are reflected in this parameter.

Main losses are dissipated in storage. These losses depend on:

- Temperature difference between the temperature of storage and ambient temperature
- Shape and contact area
- Duration of storage
- Insulation

2.7. Location

Another parameter that has to be considered before choosing the most suitable TES system is location available for energy storage.

The location has a great impact in costs, thermal losses and temperature stratification.

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Different TES locations will be studied in deliverable 2.2:

- Underground
    - Aquifer
    - Borehole
    - Pit
    - Tank
- Overground Tank
- Building Integration

2.8. Costs

In order to make TES installations feasible, costs of comparable systems with no TES implementation have to be considered:

- Energy costs
- Investment costs (adaptation to existing buildings or new constructions)
- Operation and maintenance costs
- Expected Big Maintenance and reparation costs

Costs have to be compared in opposition to different TES systems. A ratio comparing costs and energy stored may be used: €/kWh.

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3. Types of thermal storage systems

3.1. Existing technologies

Different types of technologies and systems exist with the purpose of storing thermal energy. The most suitable technology depending on the characteristics, availability and needs, are analysed separately. The technologies of storage are often classified in three major groups:

- **Sensible Heat Storage (SHS):** The more widely used technology. It has as major advantage the cost, which is the lowest of the three technologies. Another considerable advantage in active storage systems is that water stored may be used also as water for the heating distribution system, no heat exchanger is needed, hence no mean temperature associated and major exergy of the hole system available.
  On the other hand SHS has the lowest energy density and has a limited range of temperatures.

- **Latent Heat Storage (LHS):** It is a technology already in use for multiple applications. As major advantages, LHS possess a considerably higher energy density and are available for bigger temperature range. The major disadvantages are the cost, the existing environ problems and in active storage systems the need of a heat exchanger between heating water.

- **Thermochemical Heat Storage (TCHS):** This technology is not yet commercially expanded. Most of the thermochemical materials are still in research projects. The major advantages are the highest energy density and the wide range of temperature usage. Major disadvantages, additionally to its commercial use, are the cost, the environ problems and as in LHS the need of a heat exchanger in active systems.

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The state-of-art of each type of technology relative to energy density and temperature usage range are presented in the chart below:

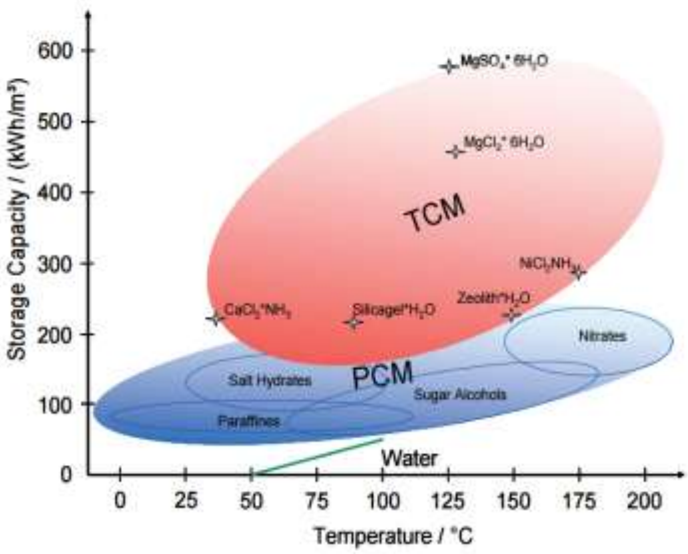

Figure: Storage Capacity vs Temperature of phase-change materials (PCM), thermo-chemical materials (TCM) and Water (source IEA-ETSAP and IRENA)

Each of the three groups of thermal storage technology have a variety of storage technologies that are presented in the chart below and that will detailed and analysed in the current document.

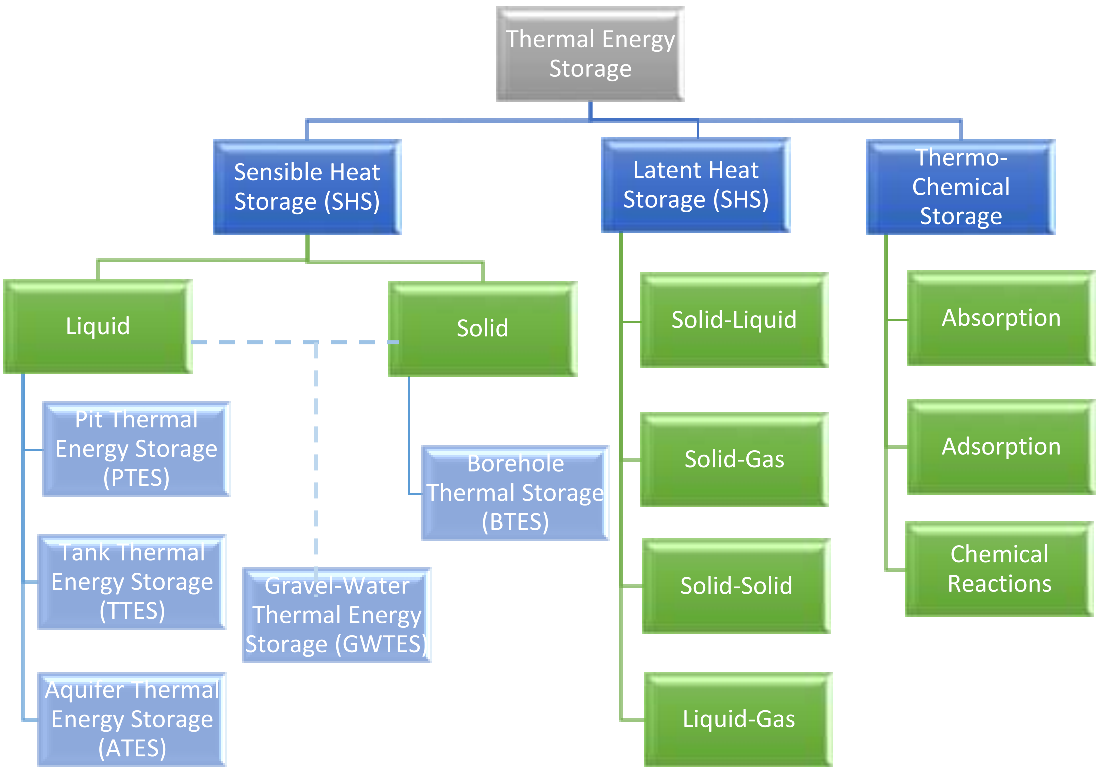

Figure: Classification of different technologies of storage (Source: Veolia)

Below are described different projects regarding existing technologies:

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The **FP7 MESSIB project** (GA No. 211624), about Multi-source Energy Storage Systems Integrated in Buildings, investigated four different technologies for electric and thermal storage: a flywheel, a redox-flow battery, a ground heat exchanger (GHEX), and phase change material (PCM). The two thermal storage technologies which were analysed and tested concern a GHEX in a 80 to 100 m deep borehole using phase change slurry (PCS) as an alternative circulation medium, and new PCM material and component developments such as micro-encapsulation of salt hydrates, and PCM boards integrated in interior walls and ceilings.

The ground heat exchanger (GHEX) development in the MESSIB project has very different characteristics compared to the CHESS-SETUP and is not using phase change slurry (PCS) as an alternative circulation medium. The **H2020 TESSe2b** project (GA No. 680556), about Thermal Energy Storage Systems for Energy Efficient Buildings, seems more related to the MESSIB ground heat exchanger, developing a high efficiency PCM tank, enhanced PCM borehole heat exchanger, nano-composite enhanced paraffin PCM, a protective thin film coating against corrosivity of salt hydrates, and a compact modular tank including a high performance heat exchanger.

The phase change material (PCM) outcomes in the MESSIB project, about micro-encapsulation of salt hydrates, and PCM boards integrated in interior walls and ceilings, also have very different characteristics compared to the CHESS-SETUP heat storage tanks. PCM applications need for example at least several hundred upload and unload cycles to equal the energy consumption and related CO2 emission to produce the PCM itself, which is a characteristic cycles number for daily storage in interior boards, but especially critical for long(er) term heat storage tanks, such a seasonal heat storage tanks with one upload and one unload per year only.

The Thermo Chemical Material (TCM) Technology Readiness Level (TRL) is much lower compared to alternatives such as PCM systems for example, and is not part of the MESSIB project, or the CHESS-SETUP pilots. The **H2020 CREATE** project (GA No. 680450) about Compact Retrofit Advanced Thermal Energy storage, seems more related to TCM, and aims to develop and demonstrate a heat battery for the existing building stock to reach at least a reduction of 15% of the net energy consumption with a potential Return-On-Investment (ROI) shorter than 10 years. Novel high-density materials will be used in order to limit the use of available space to a maximum of 2.5 m3 TCM, with an energy density of more than 1.5 GJ/m3 (420 kWh/m3).

3.2. Active and passive thermal energy storage systems

Heat energy storage systems may be classified in active and passive systems, depending on the existence of regulation and control for energy charging and discharging.

The forced convection heat transfer of the energy storage system is the main characteristic of an active thermal storage system. This system uses one or two tanks as storage media.

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Active systems also possess auxiliary mechanical components such as pumps and valves that consume auxiliary energy. Usually active systems are more complex and expensive that passive systems.

Passive systems are usually integrated in buildings as a support to match energy demand and energy production. They neither require a distribution energy system nor active control and regulation system.

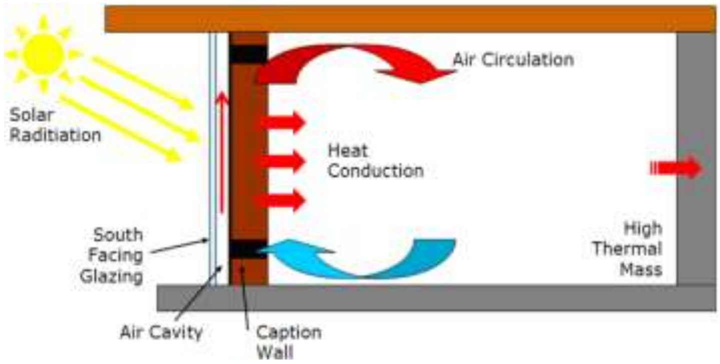

Figure: Example of passive heat storage in a caption wall

In some systems it may be found a combination of active and passive systems. One example of a combined system is masonry heaters connected to a heating distribution system.

A system with thermal or PVT panels and heat pumps requires an active storage system. Therefore, in the Chess-Setup project the analysis will be focused on active storage systems.

3.3. STES and Buffer/daily storage

The storage duration (yearly, monthly, daily or hourly) is a key factor in order to define the most suitable solution for heat storage.

In this deliverable, two storage systems are addressed: long term storage (seasonal storage) and short term (buffer/daily) storage. Different configurations or operation modes can be applied, but the basic performance consist on a slow warming up (high inertia) of the seasonal storage throughout the solar panels and use the heat pump to heat the buffer tank in a very efficient way (using the seasonal storage as a cold focus).

The two types of storage have been defined and are going to be studied:

- Seasonal Thermal Energy Storage (STES): The biggest energy storage system. It is projected to be charged when heating production is higher than the heating demand (mainly during high sun-light radiation periods of late spring season, summer season and early autumn season).

  The temperatures of the seasonal storage may oscillate between 15 and 90 Celsius degrees. Due its high inertia, the temperature varies very slowly. The

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thermal seasonal storage is not used to supply directly the energy to the building.

It will be connected directly or through a heat exchanger to thermal/PVT panels in the charging side. In the discharging side it will be connected to the heat pump evaporator.

STES require huge amounts of storage material it is very common to utilize very cheap materials; e.g. for liquid: water or oils and e.g. solid: like rocks or sands as the storage medium. Although such systems have been constructed and demonstrated, it is challenging to make them cost effective. Well-designed systems can reduce initial and maintenance costs and improve energy efficiency. Economically justified projects can be designed using annual storage on a community-wide scale, which could reduce cost and improve reliability of solar heating.

- Buffer/daily Energy Storage: A small energy storage system. Multiple purposes may be applied to this storage system. In the Chess-Setup project, the main purpose is to stabilize the heat pump condenser side, therefore increase the C.O.P (Coefficient of Performance) and optimize the electricity consumption. It may also be projected to be charged during low electricity costs' period and to flatten electricity power consumption.

  The buffer contains energy at the top at the temperature of usage, energy is used directly. While temperature in the seasonal storage will oscillate, in the buffer tank it will be more stable during whole year.

  The most common solution for buffer tanks is water, as it's cheap, may be stratified, easy to implement and have suitable properties for the operation conditions of the tank. Temperature of storage will have a similar temperature than charging and discharging.

  In case of having PCM or TCM storage, a heat exchanger will be needed, therefore the charging temperature will have to be around 5ºC higher than storage temperature, whereas discharging temperature is going to be around 5ºC lower than storage temperature.

  Particular cases of PCM or TCM buffer/daily storage may be its use for conventional district heating and for domestic hot water. As explained in section 2.2.3, the temperature required in conventional district heating will be 70-90ºC, then in case of having PCM storage, a storage of 75-95ºC will be required. On the other hand for domestic hot water production (DHW), the needed

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temperature is ≥ 60ºC, if an additional external or internal heat exchanger is needed, the temperature of storage will have to be around 70ºC.

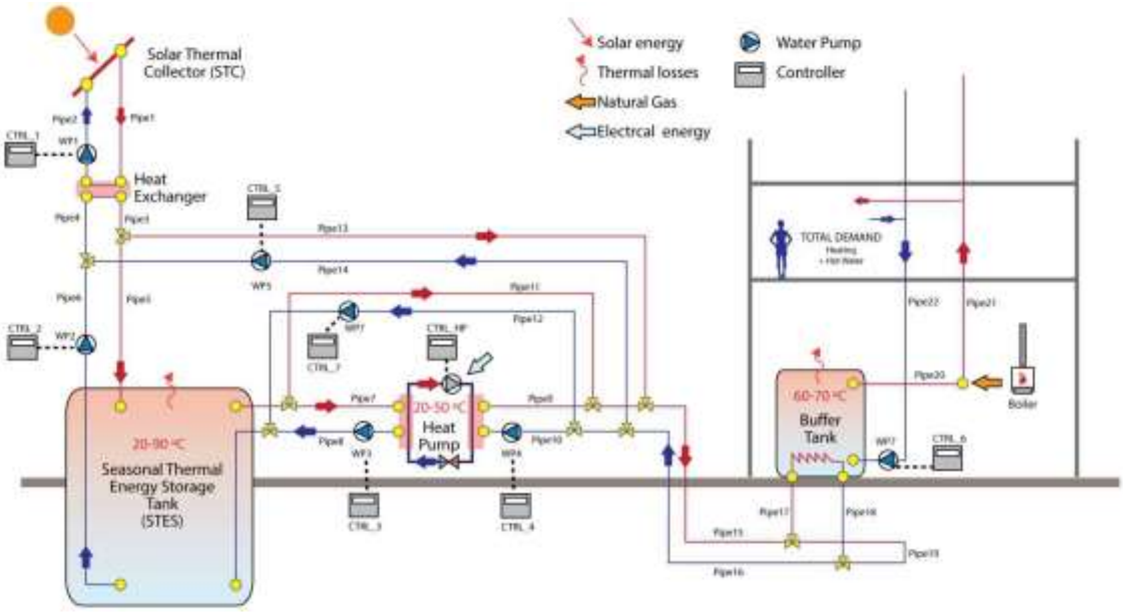

Figure: STES and Buffer/daily storage in simulated installation (Source: BCN Ecologia)

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4. Sensible Heat Storage

4.1. Definition

Sensible heat storage (SHS) is a type of thermal storage that is based in the change of thermal storage capacity of an insulated material due to the temperature variation and without phase change. Hence, the storage capacity will depend on the thermal properties of the material (mainly its specific heat), the amount of material (volume) and storage temperature (range between maximum and minimum temperature).

4.2. Classification of SHS

SHS can be classified according to the storage duration or storage material (solid, liquid or gas):

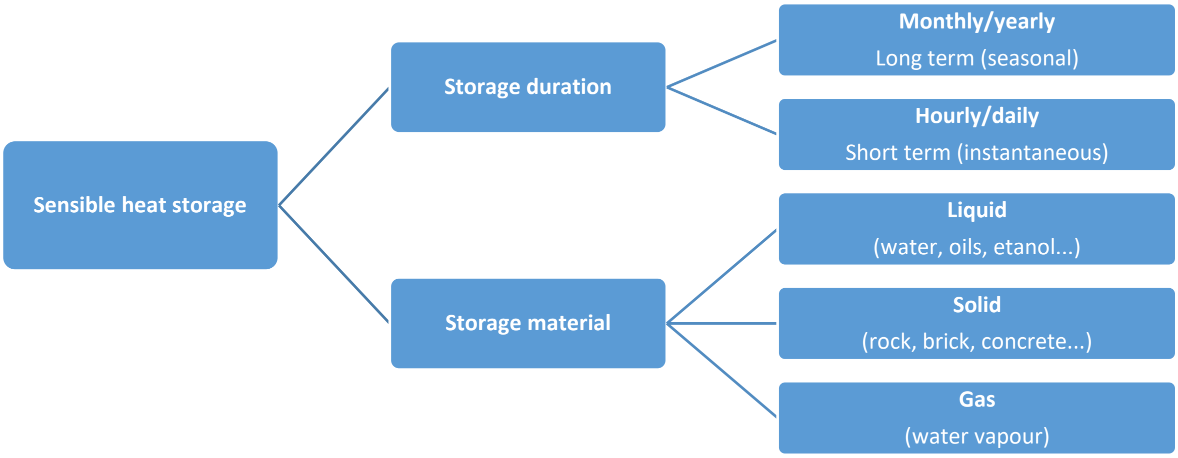

Figure: classification of sensible storage systems. (Source: BCN Ecologia)

4.3. Material properties

Next table shows the most common used sensible storage materials, including information about their storage temperatures, density, storage capacity and heat conductivity.

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Material	Type	Temperature range (ºC)	Density (kg/m³)	Capacity (kJ/kgK)	Capacity (kJ/m³K)	Heat Conductivity (W/mK)
Stone	Solid	300	1,700	1.3	2,210	
Firebrick	Solid	700	1,820	1	1,820	0,22
Reinforced concrete	Solid	400	2,200	0.85	1,870	0.99-1.09
Molten iron	Solid	400	7,200	0.56	4,032	
Water	Liquid	0-100	1,000	4.19	4,190	0.56-0.66
Mineral heat oil	Liquid	300	770	2.6	2,002	
Synthetic motor oil	Liquid	350	900	2.1	1,890	0.15
Ethanol	Liquid	<78	790	2.4	1,896	0.168
Propanol	Liquid	<97	800	2.5	2,000	0.15
Butanol	Liquid	<118	809	2.4	1,941	0.153
Molten salt (nitrate)	Liquid	450	1,825	1.6	2,920	
Steam (5 bar)	Gas	400	0.326	2.1 kJ/kg	-	0.016
Steam (5 bar)	Gas	140	0.536	4.3 kJ/kg	-	0.016

Table: Characteristics of main sensible storage materials. (Source: Gil, A., Bales, C., Cabeza,L. and engineersedge)

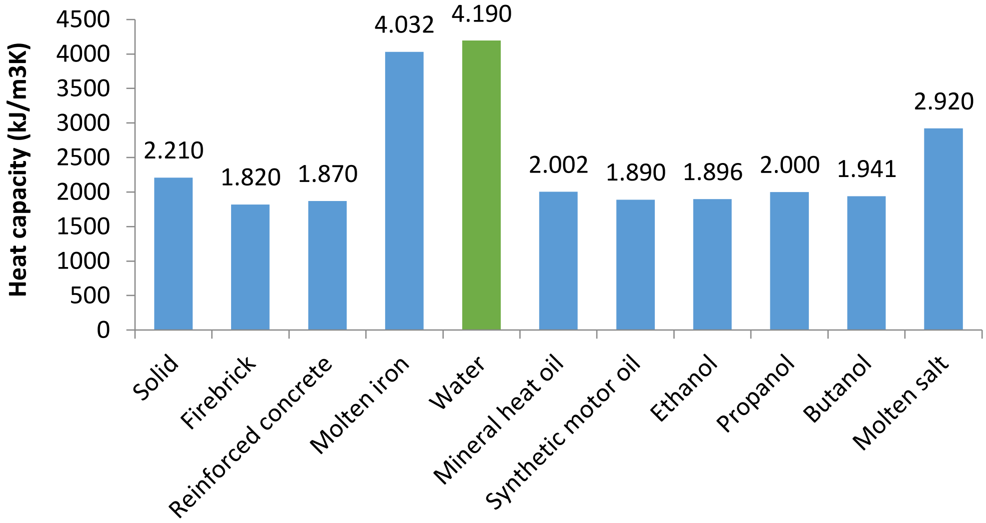

Figure: Heat density of main sensible storage materials. (Source: BCNecologia)

These parameters are important in order to select the most suitable storage material, but also have to be considered other issues as the material cost, operation and maintenance or the environmental impact.

Nowadays, with the reasonable cost and simple implementation, **water storage** technology is the most common used material for seasonal thermal storage. Water has

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the highest specific heat capacity, thus the highest energy density, almost no degradation under thermal cycling, good compatibility with most of containment material, good stratification, good heat transfer and most importantly, widely available and cheap. Water storage solutions have certain degrees of stratification, depending on the size, volume, geometries, water flow rates, and circulation conditions of the storage system. In the other side it has some disadvantages as the low temperature range of operation or corrosivity.

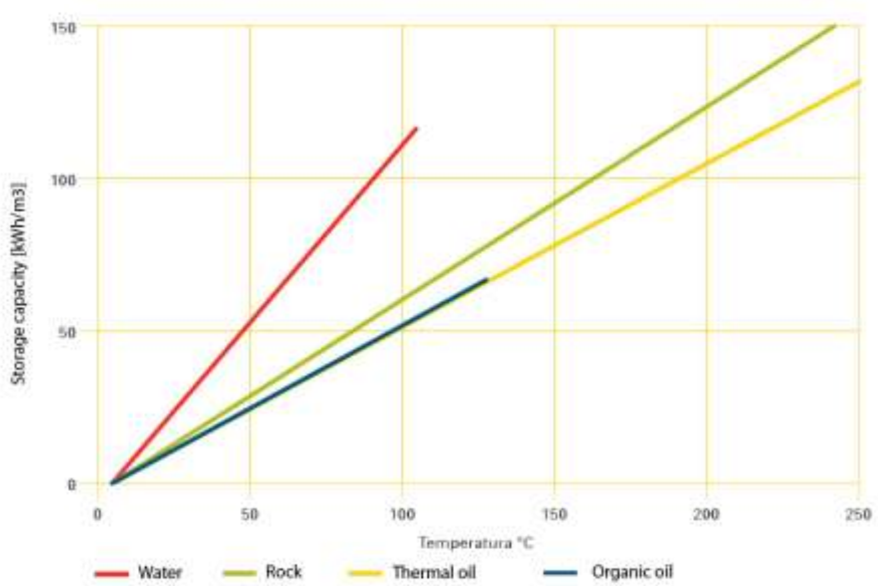

Figure: Storage capacity (kWh/m^3) related to storage temperature (ºC) (Source: Gas Natural)

In the case of solids, the material is invariably in porous form and heat is stored or extracted by the flow of a gas or a liquid through the pores or voids.

4.4. Configuration of Seasonal Sensible Heat Storage (SSHS)

4.4.1. Introduction

Generally speaking, there are four types of sensible seasonal thermal energy storage solutions: tank thermal energy storage (TTES), pit thermal energy storage (PTES), aquifer thermal energy storage (ATES) and borehole thermal energy storage (BTES). Among these four storage solutions, TTES, PTES and ATES belong to the type of sensible water thermal storage; BTES belongs to the type of sensible solid storage. Also in PTES is commonly used a combination of gravel and water as a storage material so the gravel contribute to the structural support of the deposit (GWTES).

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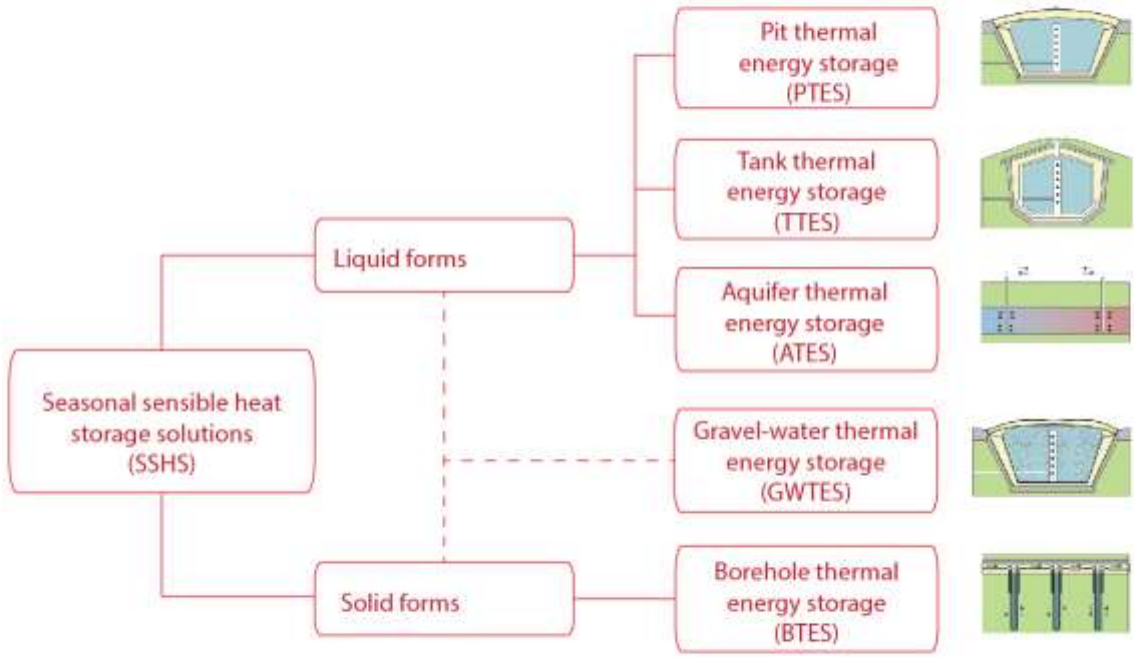

Figure: Seasonal sensible thermal energy solutions. (Source: BCNecologia)

4.4.2. Tank Thermal Energy Storage (TTES)

The tank thermal energy storage (TTES) has the widest range of utilization possibilities and can be built almost independently from geological conditions. Seasonal TTES usually have a tank construction built of reinforced concrete, heat insulated at least in the roof area and on the vertical walls. It is usually built as steel or reinforced pre-stressed concrete tank, fully or partially buried in the ground.

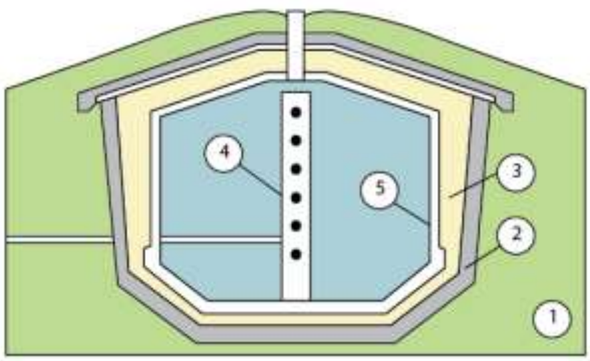

Figure: Tank thermal energy storage system.
[1]soil; [2] reinforced concrete; [3] insulated layer; [4] stratification pipe; [5] steel layer (Source: BCNecologia)

The storage material used in TTES is water, which gives good values concerning specific heat capacity and possible power-rates for charging and discharging, being the most favourable solutions from the thermodynamic point of view. With unpressurised tanks, the storage medium can be heated up to 95ºC. If the tank is under pressure and is

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steam-tight, significantly higher temperatures can be achieved, but construction costs are also higher.

The temperature stratification is carried out automatically as hot water is less dense and therefore rises. However, to prevent any mixing of the layers, a stratification device can be used for charging in accordance with its temperature. Stratification allows increasing the efficiency of the heat pump and solar collectors.

To be efficient water tank should have storage volumes over 1,000 m3, otherwise the heat losses are too high. Usually TTES are between 2,750 m3 and 12,000 m3.

Figure: Internal aspect of a big TTES (6,000 m^3). Ackermannbogen (Munchen)

Figure: Construction of a big TTES (12,000 m^3). Friedichshafen (Germany, 1996)

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Usually water tanks are situated underground to reduce the thermal losses. They can be integrated as a hill to be transitable. The conditions of the subsurface should be stable and, if possible, have no groundwater at a depth of 5 m to 15 m.

Figure: Integration of a thermal storage hill into the landscape (Source: Raum)

The first TTES (Rottweil, Friedrichshafen and Hamburg) have been built with an additional inner stainless-steel liner to guarantee water tightness, to protect the heat insulation on the outside and to reduce heat losses caused by steam diffusion through the concrete wall. With the development of a new high density concrete material it was possible to build the store in Hannover without an inner steel-liner.

The older stores have been built with only two levels for charging and discharging (on top and at the bottom). In Hannover was implemented a store with a third device which is located below the upper third of the storage volume. This provides the following advantages during operation: it enables an optimized stratification in the store because low temperature heat can be charged into the store without disturbing higher temperature layers on top of the store. In addition simultaneous charging and discharging of the store at different temperature levels becomes possible. For the heat insulation a granulated foam glass was used in Hannover, which is filled into textile bags at the side walls. The advantage of this material compared to the former used mineral wool is a faster and easier installation procedure and a better drying performance if it becomes wet. In Hannover, the insulation layer is protected by a steam barrier because the high density concrete is not absolutely tight against steam diffusion.

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4.4.3. Pit thermal energy store (PTES)

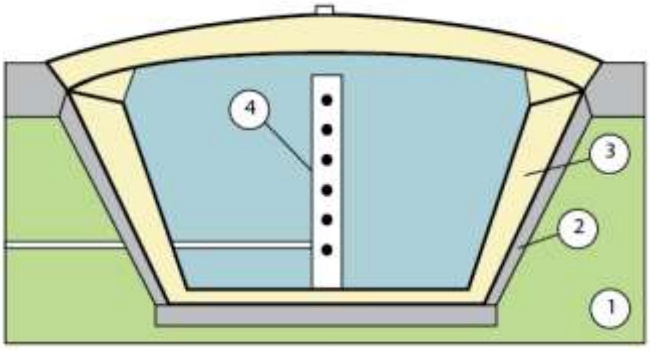

Figure: Pit thermal energy storage (PETS) system.
[1]soil; [2] reinforced concrete; [3] insulated layer; [4] stratification pipe (Source: BCNecologia)

This system contains buried accumulators without static elements for its construction. Basically this system consists in a large and enclosed artificial pond where the sides are covered with thermal insulation material. The covered part represents the most complex and expensive part. Generally no support structures are used, but this remains floating above the accumulated water. PTES are dug into the ground, but close to the surface (depth of 5 to 15 meters) in order to reduce excavation costs. The slope angle of the side walls depend on the nature and density of the supporting soil.

If parking spaces of buildings are intended to be built above the store, PTES are preferable solution due to their sold fillings that can be individually customized.

The use of insulating material on the sides of the pond is only recommended in applications with temperature above 40°C work. Maximum temperatures up to 85°C can be stored, depending on the temperature stability of the inner sealing foil. Compared to TTES systems, PTES are rather flat and have large surface area, which means higher thermal losses and lower stratification.

In the PTES case water is the most used storage material, but gravel-water mixture (GWTES), water-soil or water-sand mixture can be used. For systems whose storage material is water storage capacity is between 60 and 80 kWh/m3 (with temperatures ranges between 50 and 70ºC), whereas in systems using solid mixture of water this is between 30 and 50 kWh/m3. That means that the volume of the store has to be approximately 50% bigger compared to a water PTES to store the same amount of heat at the same temperature levels. Also the stratification will be lower with a solid mixture as thermal conductivity is higher. Nevertheless, a mixture of water and solid can reduce the cost and simplify the tank construction, since it increases the load capacity of the roof resting on it.

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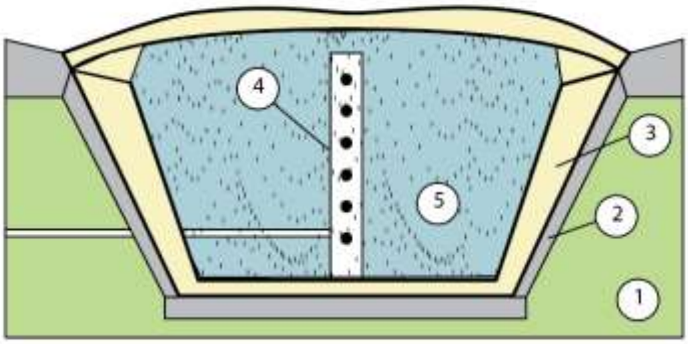

Figure: Gravel-water thermal energy storage system.
[1]soil; [2] refoirced concrete; [3] isulated layer; [4] stratification pipe; [5] gravel (Source: BCNecologia)

Figure: Pit storage construction in Eggenstein, 2008 (4,500 m³).

	Gravel	Water
Thermal stratification	-	+
Performance	~	+
Inertia	+	-
Usability of the store roof	+	~
Simplicity of construction	+	-

+ high / ~ moderate / - low

Table: Comparison of storage materials properties. (Source: Solites)

Usually PTES are over 1,000 m3, but in Vojens (Denmark) has already been built a tank with 200,000 m3.

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Figure: Construction of the PTES in Vojens. (Source: DTU civil engineering)

4.4.4. Borehole Thermal Energy Storage (BTES)

In borehole thermal energy storage (BTES), heat is stored directly into the ground. BTES do not have an exactly separated storage volume. The heat is transferred to the underground by means of conductive flow from a number of closely spaced boreholes.

The heat capacity and storage temperature will depend on the ground composition. BTES can achieve heat densities of 15-30 kWh/m3 (20-25% of storage capacity of water). They are especially useful in a subsurface with a high heat capacity and impermeability, e.g. water-saturated clays and rocks. These are favourable because they are rarely subjected to groundwater movements that would cause heat losses.

BTES should be installed for economic reasons only in well drillable subsurfaces. It should be ensured that no groundwater leaks out due to heat losses in the ground drilled through. Extensive geological preliminary investigations must be carried out in any event.

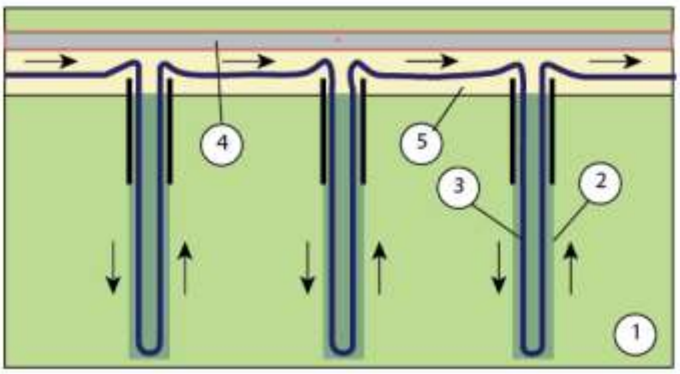

Figure: Borehole thermal energy storage (BTES) system.
[1]soil; [2] grouting; [3] borehole heat exchanger; [4] covering layer; [5] heat insulation (Source: BCN Ecologia)

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There are two basic principles, open and closed, being used to transport the heat carrying medium in and out of the holes. The two principles are illustrated in next figure.

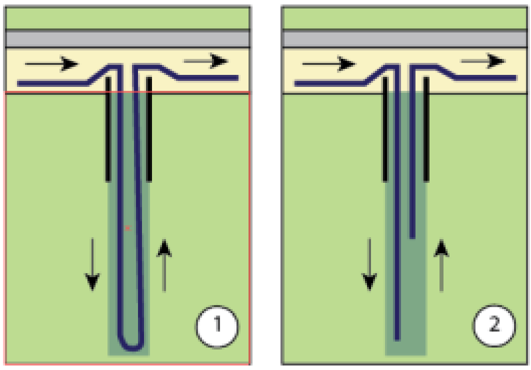

Figure: Basic principles for borehole thermal energy storage
[1] closed system; [2] open system (Source: BCN Ecologia)

In the open system is the inserting pipe placed with its outlet close to the bottom of the hole, whereas the extraction pipe has its inlet opening close to the top of the hole, but below the ground water table. The closed system uses u-pipes, and this means that the heat medium is pumped in a closed circuit, eliminating a number of potential problems with regard to water chemistry etc. that are inherent in the open system. The u-pipes act as a heat exchanger between the heat/cold carrying medium and the surrounding rock.

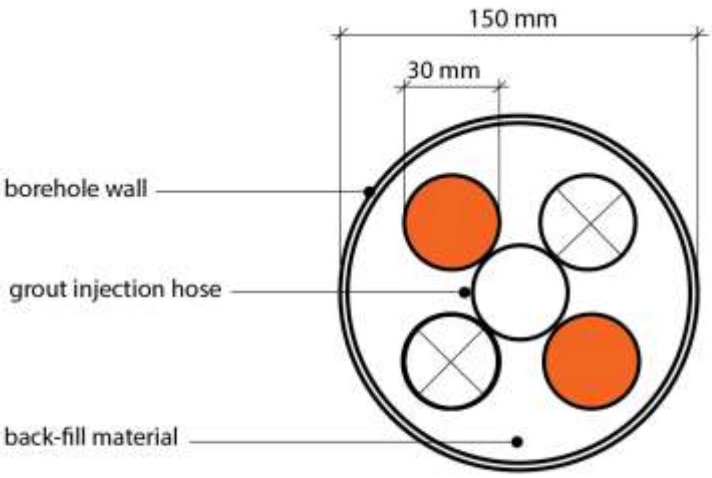

Figure: Diagrammatic cross-section of a geothermal probe (source: Solites)

Heat is charged or discharged by vertical borehole heat exchangers which are installed into a depth of 30–200 m below ground surface. At charging, the flow direction is from the centre to the boundaries of the store to obtain high temperatures in the centre and lower ones at the boundaries of the store. At discharging the flow direction is reversed.

The boreholes have diameters of about 0.1 m – 0.2 m and require a horizontal gap of 1.5 m – 3 m between each of them. To make them energetic and financially feasible

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volumes larger than 20,000 m3 are required. Existing cases are between 9,350 m3 (Attenkichen) to 37,500 m3 (Crailsheim) and even up to 63,300 m3 (Neckarsulm).

Figure: Geothermal borehole (source: Solites)

For structural and economic reasons, this type of store can be insulated only at the top. It is important to protect this insulation against rainwater. Therefore, a sheet that is waterproof at the top and open to allow vapour diffusion at the bottom is designed for use as the insulating layer. This foil layer has gradient enabling rainwater to drain from it. A drainage layer and soil are put on top of it. Finally, humus is applied, so that the thermal energy store is completely under ground level.

Heat or cold is delivered or extracted from the underground by circulating a fluid in a closed loop through the boreholes. The fluid consists of water, which is mixed with glycol or alcohol to allow the system to work below the freezing point, if so required.

During periods of heat recharge warm water is pumped through the pipes and the rock mass heats up to produce a heat reservoir. During periods of heat abstraction cold water is pumped through the same boreholes to exploit the stored heat. Hence BTES systems work in a cyclic mode. The efficiency of the heat exchange will improve with higher thermal conductivities, but the rate of heat conduction away from the reservoir (hence heat loss) will increase with higher thermal conductivities. Therefore the important parameters for BTES are medium thermal conductivities, high specific heat and no groundwater flow.

BTES does not have vertical temperature stratification. That is because the heat transfer is mainly driven by heat conduction and not by convection. At the borders the temperature decreases because of the heat losses to the surroundings. The horizontal stratification is supported by connecting the supply pipes in the centre of the store and the return pipes at the borders.

An important issue in the design of underground seasonal storage systems using borehole heat exchangers is to find cost-effective methods to construct the borehole thermal energy storage field so that heat can be injected or extracted from the ground

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without excessive temperature differences between the heat carrier fluid and the surrounding ground. As a result of the limited thermal conductivity the heat losses are rather moderate and storage efficiencies of 70% can be reached. In contrast good thermal contact between the heat exchangers and the ground is required to allow a good heat transfer rate per unit area of the heat exchanger tube.

The most important parameters influencing the borehole thermal resistance are the thermal conductivity of filling material, the number of pipes, pipe position and the pipe thermal conductivity. Some important parameters for a successful BTES are: rock with high specific heat, medium to high thermal conductivity, and compact rock mass with (virtually) no ground water flow. Other important parameters are the type of rock including grain size and the types of minerals. Suitable geological formations for this kind of heat storage are e.g. rock or water-saturated soils.

The advantages of BTES are the extend ability and the lower effort for construction compared to TTES and GWTES. This also leads to lower costs. On the other hand **the size of a BTES has to be three to five times higher compared to a TTES for the storage of the same amount of heat**. This is because of the reduced heat capacity of the storage material and the smaller power rates for charging and discharging due to the heat transfer in the borehole thermal energy storages. Often an additional buffer store is necessary as well.

Seasonal storage in the ground, using ground heat exchangers, seems to be favourable from technical and economical point of view. Depending on the temperature level, the thermal energy is extracted either by a heat pump (low temperature ground storage < 40°C) or directly (high temperature ground storage, 40-80°C) and delivered to the customers. The thermal performance of such systems is influenced by the heat and moisture movement in the area surrounding the heat exchangers.

The performance factor of heat pump supported BTES systems will normally be in the range 4-5, depending on the amount of cold produced in the system. The cold production (free cooling) in itself is normally around 20-30. The pay-back time for these kinds of systems ranges between 5 and 10 years; depending on size and other circumstances. This is significantly higher than for ATES, but on the other hand, the operational risks are much lower.

A major challenge facing BTES systems is their relatively low heat extraction efficiency. Annual efficiency is a measure of a thermal energy storage system's performance, defined as the ratio of the total energy recovered from the subsurface storage to the total energy injected during a yearly cycle (Dincer and Rosen, 2007). Efficiencies for the first 6 year of operation of the BTES system at the DLSC range from 6 to 54%.

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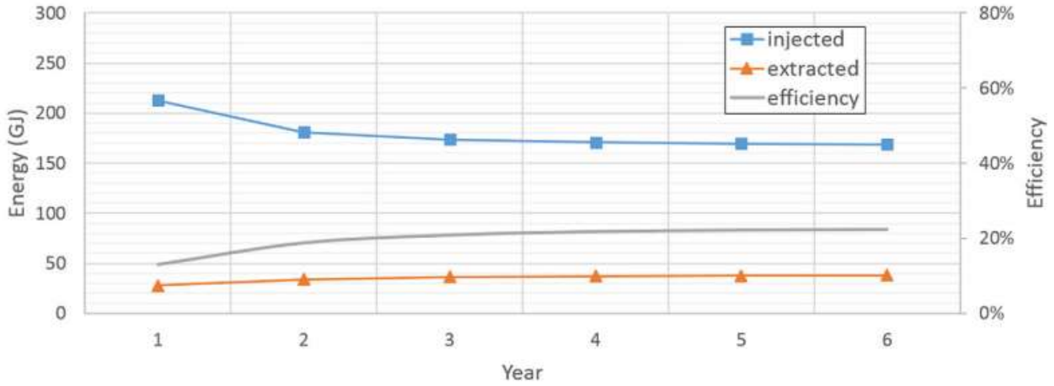

Figure: Simulated energy injection and extraction and heat extraction efficiency of the modeled borehole thermal energy storage system base scenario with time. (Source: Catolico N. et al,)

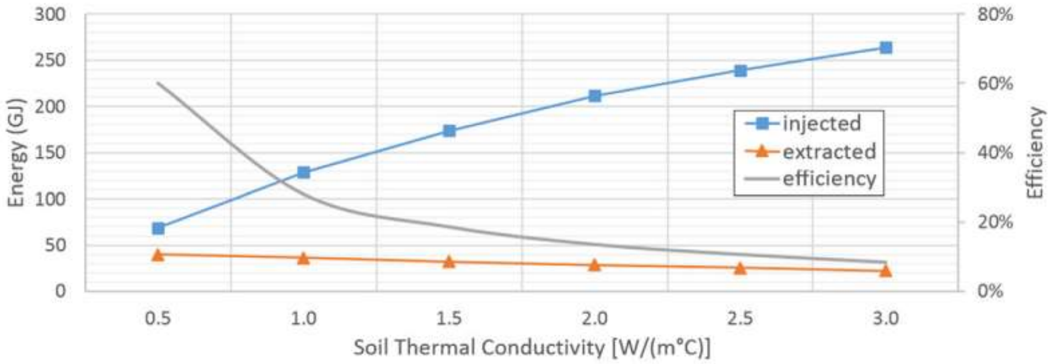

Figure: SImulated energy injection and withdrawal and heat extraction efficiency of the borehole thermal energy storage system at various soil thermal conductivity values. (Source: Catolico N. et al,)

Few studies have investigated the impact of hydrologic parameters on the efficiency of BTES. Common guidelines require a subsurface that is drillable, of high heat capacity, and with low hydraulic conductivity (Schmidt et al., 2003; Pavlov and Olesen, 2012). Several factors may affect BTES system performance, including the volume and geometry of storage space, the number and dimensions of boreholes, the injection–extraction scheme, and the soil and rock mechanical, hydrological, and thermal properties (Ohga and Mikoda, 2001; Dehkordi and Schincariol, 2014b; Başer and McCartney 2015). The influences of these factors are poorly understood, and no specific parameter guidelines have been suggested for enhancing the efficiency of BTES systems. Advancements in the understanding of the specific effects of these parameters are needed because improved efficiency would greatly increase the economic viability of BTES technology.

4.4.5. Aquifer Thermal Energy Storage (ATES)

ATES can be distinguished in water saturated porous aquifers in sand, gravel or eskers and fractured aquifers in limestone, sandstone, igneous or metamorphic rock. ATES which are filled with groundwater have high hydraulic conductivity. If there are impervious layers above and below and no or only low natural groundwater flow, they can be used for heat (and cold) storage.

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It will be required to build two reversible wells (or group of wells) one will be the cold sink and the other the warm. During warm season cold water is removed from the cold sink, heated by the solar energy or other energy sources and sent to the hot sink. During cold season the cycle is reversed; the water is removed from the hot sink, cooled by the heat pumps (or heat exchanger) and sent to the cold sink.

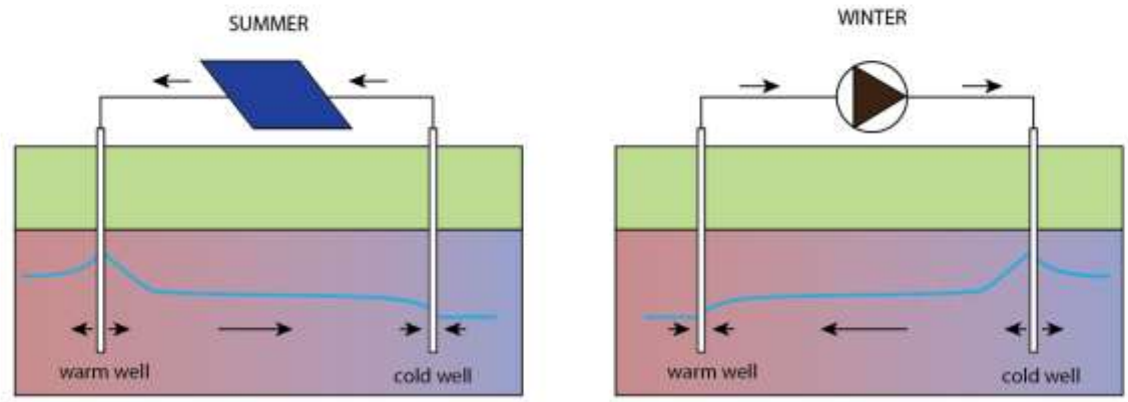

Figure: Operation of ATES

Because of the different flow directions both wells have to be equipped with pumps, production- and injection-pipes. *(Source: BCNecologia)*

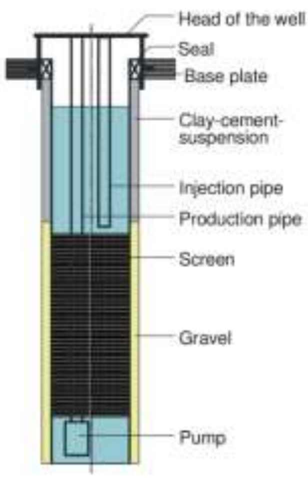

Figure: Layout of a well for charging and discharging.
(Source: Geothermie Neubrandenburg GmbH)

It is not possible to insulate the aquifer so it is recommended to be implemented in systems higher than 20,000 m3 to reduce the specific heat losses and at temperatures lower to 50 °C, also in order to reduce the thermal impact in the aquifer. At this temperature water treatment can be necessary as chemical and biological processes can lead to deposition, corrosion and degradation in the system.

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The storage capacity of ATES are between 30 and 40 kWh/m3, lower than TTES and PTES because the storage temperature is lower and the water is mixed with other solids with lower specific heat capacity.

ATES can be also used for cooling purposes in reversible geothermal systems. In that case during the heating season, water is extracted from the warm well, cooled and re-injected into the cold well. The circulation is reversed during the cooling season, so that cold water is extracted from the cold well, heated and re-injected into the warm well. The systems are often designed to cover the total cooling demand of the building, while the heat production normally covers 50% of the load and some 70-80% of the energy. This is due to the heating demand use being higher than cooling demand in most of the European locations and buildings. Therefore, by combining the reversible geothermal operation mode with solar thermal panels it will be possible to cover the whole heat demand.

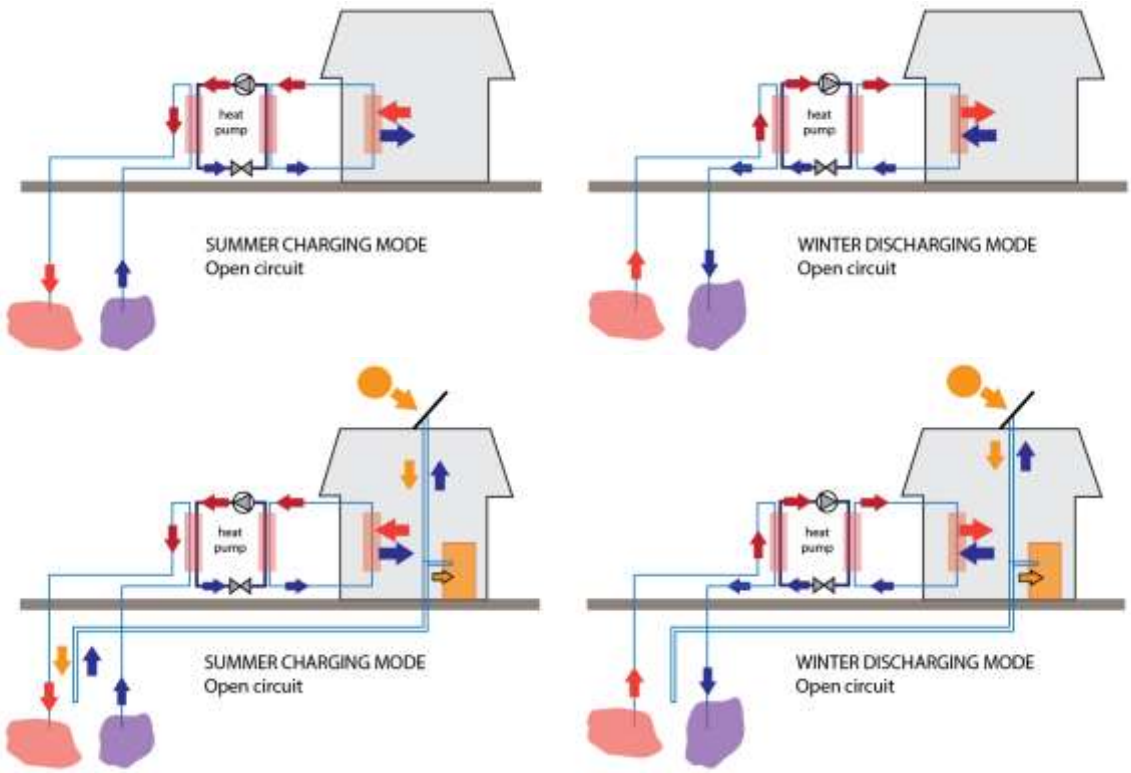

Figure: Geothermal system with seasonal thermal storage in aquifer without solar contribution (up) and with solar contribution (down). (Source: BCNecologia)

4.4.6. Modular hot water storage tanks

Another option is the implementation of modular storage tanks. These types of accumulators are suitable to be integrated in existing buildings. This system can be

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more expensive and its volume is not as big as the common seasonal storage systems but offers some interesting advantages:

- Less tank pressure
- In situ construction
- Cubical shaped tank
- Space efficiency
- Modular concept
- Very flexible design
- Easy to install
- Well insulated
- Perfect temperature stratification
- Prefabricated containers
- Polymeric tank materials
- Cost efficient by industrial manufacturing of modules

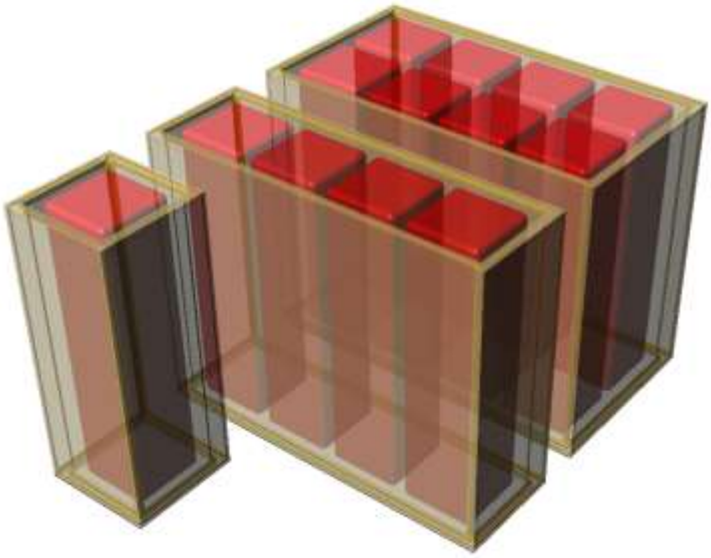

Figure: Hot water storage tanks modular concept. (Source: BCNecologia)

Figure: Hot water storage tanks. (Source: Universitat Stuttgart)

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4.4.7. Table summary of seasonal SHS systems

TTES and PTES have the most favourable conditions for optimizing the solar surface versus storage volume ratio and minimizing heat losses. The main limitation of these systems are that requires stable ground conditions as the tanks are installed at 5 to 15 meters underground.

Next tables show the main characteristics for each system:

System	depth (m)	Capacity (kWh/m3)*	efficiency (%)	Tmax (ºC)	Cost (€/MWh)
Hot Water Thermal Energy Storage (TTES)	5-15	60-80	50-90	90	8-10
Pit thermal energy store (PTES)	5-15	60-80	50-90	80	8-10
Gravel-Water Thermal Energy Storage (GWTES)	5-15	30-50	-	90	-
Aquifer Thermal Energy Storage (ATES)	-	30-40	50-90	50	5-60
Borehole Thermal Energy Storage (BTES)	30-100	15-30	50-90	60	10-140

Table: Basic technical parameters. Temperature range between 50ºC and 70ºC (Source: Gas Natural)

Next table shows the main geological requirements for each system:

TTES/PTES	Stable ground conditions Preferably no groundwater
ATES	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 temperature Aquifer thickness of 20 – 50 m
BTES	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

Table: Main geological requirements for seasonal storage systems (Source: Solites)

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4.5. Existing Seasonal Sensible Heat Storage (SSHS)

4.5.1. Examples of SSHS in Europe

Solar thermal seasonal storage systems has been studied and implemented in several cases, especially in northern countries and integrated at district level. Some of the well-known projects are located in Germany, Sweden and Denmark. First projects are dated in 90's years.

Storage type	Total heat demand	Total heat demand	Solar collector area	Storage volume	Solar fraction	Solar Supply	Solar perform.	Max temp	Volume/ area	Solar heat cost
	GJ/year	MWh/ year	m²	m³	%	MWh/ year	kWh/year per m² collector	°C	m	MWh-1
Water tank										
Hamburg, DE	5,796	1,610	3,000	4,500	49	789	263	95	1.5	256 EU
Friedrichshafen,DE	14,782	4,106	5,600	12,000	47	1,930	345	95	2.1	158 EU
Hannover, DE	2,498	694	1,350	2,750	39	271	200	95	2.0	414 EU
Munich, DE	8,280	2,300	2,900	5,700	47	1,081	373	95	2.0	240 EU
Ingelstad, SE			1,320	5,000	14				3.8	1,900 SEK
Lambohov, SE			2,700	10,000	37				3.7	1,100 SEK
Hoerby, DK				500						
Herlev,DK	4,520	1,256	1,025	3,000	35	439	429		2.9	
Gravel-water pit										
Stuttgart, DE	360	100	211	1,050	60	60	284	85	5.0	
Chemnitz, DE	4,320	1,200	2,000	8,000	42	504	252	85	4.0	240 EU
Steinfurt, DE	1,170	325	510	1,500	34	111	217	90	2.9	424 EU
Eggenstein, DE	3,276	910	1,600	4,500	40	364	228	80	2.8	
Ottrupgaard, DK	1,630	453	560	1,500	16	72	129		2.7	
BTES										
Neckarsulm, DE	1,663	462	5,000	63,400	50	231	46	85	12.7	172 EU
Crailsheim, DE	14,760	4,100	7,300	37,500	50	2,050	281	85	5.1	190 EU
Attenkirchen, DE	1,753	487	800	10,000	55	268	335	85	12.5	170 EU
Anneberg, SE	3,888	1,080	3,000	60,000	60	648	216	45	20.0	100 SEK
Okotoks, CA	1,900	528	2,293	35,000	90	475	207	80	15.3	
ATES										
Rostock, DE	1,789	497	1,000	20,000	62	308	308	50	20.0	

Table: Technical data of CSHPSS (Source: Pavlov G. et al Seasonal Ground Solar Thermal Energy Storage - Review of Systems and Applications, 2011)

The first multifunction thermal energy store integrated to a district heating network was put into operation in Hamburg in October 1996.

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Figure: Central solar heating plant with seasonal storage (CSHPSS) in Hamburg (1996)
(Source: Solites)

Since 2010, Denmark and Germany have been developing complex multifunctional energy-supply systems for power and heat. Multifunctional storage systems allow the integration of several energy sources and applications:

- Buffering of peak loads of district heating networks.
- Decoupling of the heat supply and electricity production for Combined Heat and Power (CHP) units connected to a district heating network.
- Storage of waste heat from industrial processes.
- Bridging of downtimes of waste incinerators, biomass, biogas…
- Exploitation of electrical power for load-frequency control by converting it into heat (preferably by using a heat pump).

Research projects focus in next priorities:

- Expanding the basic knowledge required to carry out seasonal thermal energy storage.
- Implementing further pilot projects for solar thermal energy storage and the associated dissemination of the technology.
- Optimising the system based on experience gained with the pilot projects with the aim of achieving an optimum cost-benefit ratio, while taking into account all the economic and overall energy aspects.

4.5.2. Einstein project pilots

CHESS-SETUP could be taken as the continuity of other Horizon-2020 project, the EINSTEIN project. The Einstein project was focused on the development of Seasonal Thermal Energy Storage concept. Two demonstration plants were designed and built

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to demonstrate the research results of the project. Demonstration plants were built in Zabki (Poland) and Bilbao (Spain), two locations which are very different in terms of the climate and typical heating systems installed in existing buildings. In both demonstration plants, solar collectors combined with heat pumps were used as the heat source. The heat pump installed in Poland has been developed by University of Ulster.

Polish Demonstration Plant comprises a solar array of 151 m² coupled with a seasonal thermal storage system (STES) of 800 m³ which complements a gas boiler of 90 kW in meeting the space heating demands of the building. Flat plate collectors were installed on the field near the STES. Heat pump was installed in the basement of Administrative building.

The seasonal thermal storage thickness of wall is 70 cm. That great value of insulation thickness is resulting in very low heat transfer coefficient (< 0.1 W/(m²K)).

Figure: Seasonal thermal storage (800 m³) in Zabki (Poland).
It is visible the great thickness isolation of the wall (70 cm).
(Source: Einstein Project)

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Figure: Seasonal thermal storage during operation. October 2014
(Source: Einstein Project)

The Spanish demo site was installed in Bilbao near the centre of the town, in the facilities of a former paper mill than nowadays is owned by the City Hall of Bilbao, and dedicated to cultural events. The Seasonal Thermal Energy Storage tank and the whole installation are used only at building level. The installation of the equipment of the Spanish demonstration plant started in April 2014 and finished at the end of July.

The dimension of the tank is 180 m^3 volume and 6 m of diameter. The insulation of the tank has been selected in 0.55 m thickness of insulating. With this thickness, the thermal losses power (when medium temperature of the tank is 90 ºC) is around 1.1 kW.

Figure: External aspect of Bilbao tank
(Source: Einstein Project)

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4.5.3. Investment costs

The price of the system can be related to the plant size. Generally as bigger is the plant lower is the ratio between the investment cost and plant size. Smaller plants, with tanks volumes smaller than 500 m3, have costs between 450 and 500 €/m³, while in plants with tank volumes over 10,000 m³ the price is reduced significantly, achieving values of 50 €/m³. Also other factors as the soil conditions or the adopted solution will influence the final price of the plant. Therefore it's complicated to define general prices for these plants and it should be analysed for each particular project.

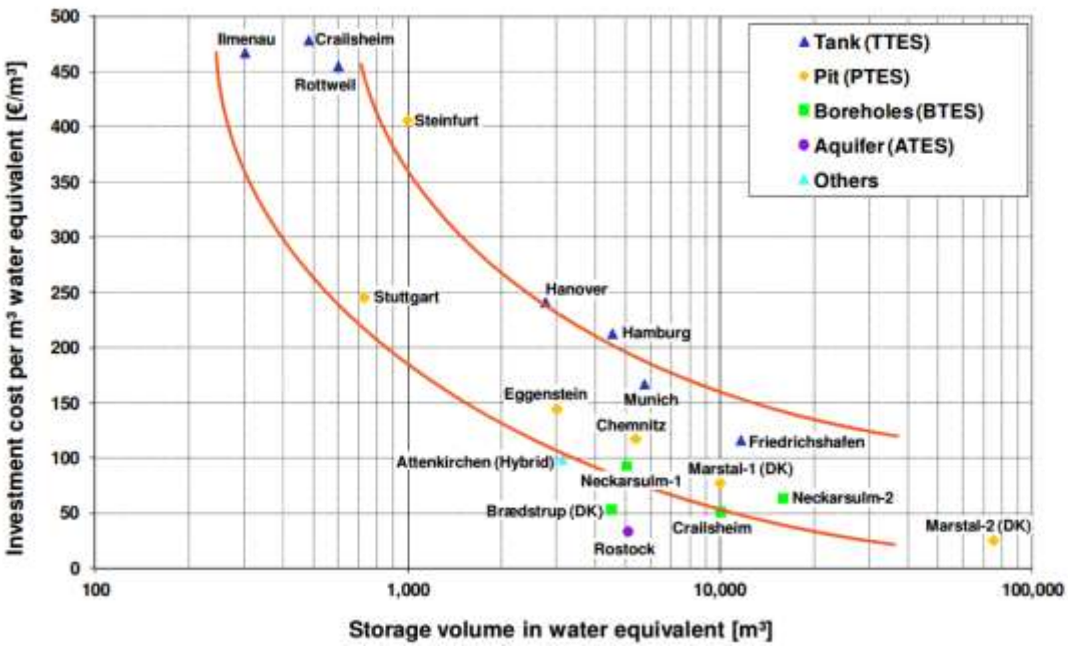

Chart: Investment cost per water equivalent.
(Source: Solites)

Next figure shows a typical cost allocation for four examples using four different storage concepts:

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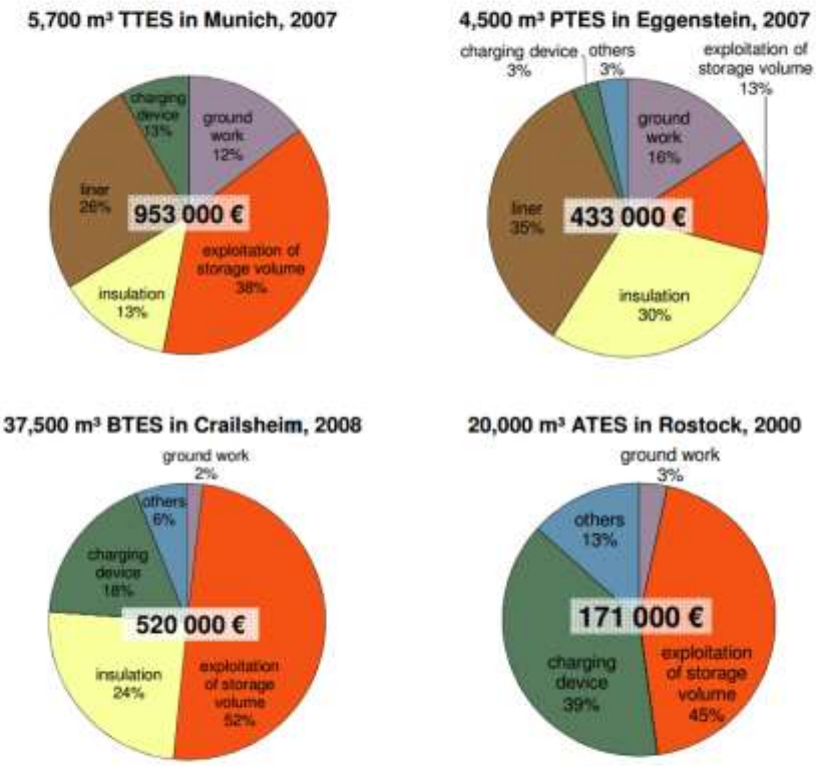

Figure: Exemplary allocation of construction cost for different storage concepts. (Source: Solites)

4.6. Advantages/disadvantages of SHS

In the following table, are shown the main advantages and disadvantages of SHS in front of other storage technologies to consider when choosing the appropiate system.

Advantages	Disadvantages
Low cost Good stratification High energy transfer No Temperature hysteresis Heat exchanger not compulsory Suitable for a wide range of temperatures No degradation Existing installations	Stable storage temperature Lower energy density Small range of temperatures Temperature hysteresis Corrosivity

Table: Advantages and disadvantages of SHS

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5. Latent Heat Storage (LHS): Phase-Change Materials (PCM)

5.1. Definition

Latent heat storage (LHS) is a type of thermal storage that has a thermal capacity that depends mainly on energy absorbed and released during a phase change material process. Therefore, the storage capacity will depend mainly on its latent heat and the amount of material (volume). Materials used in latent heat storage are referred as phase-change materials (PCM).

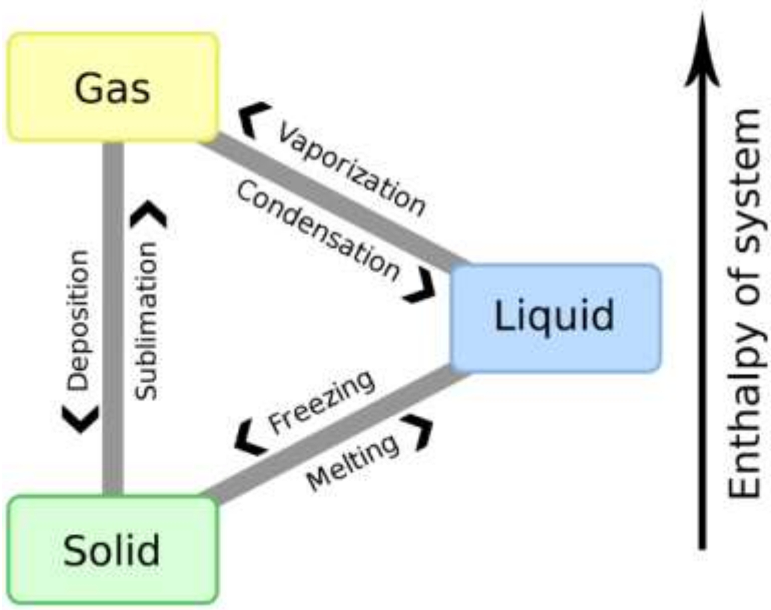

Figure: Latent phase change (Source: Adapted from Flanker)

PCMs latent heat storage can be obtained in solid-solid, solid-liquid, solid-gas and liquid-gas phase change. The most widely used phase change for PCMs is the solid-liquid change. Heat is absorbed or released when the material changes from solid to liquid and vice versa.

Many substances have been studied as potential PCM, but only a few of them are commercialized as so. The selection of the material to be used in latent heat storage is not easy. Availability and cost are main drawbacks for the selection of a technically suitable material. PCM faces some problems for its application, such as phase separation, supercooling, corrosion, long term stability, and low heat conductivity have not been totally solved and are under research.

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5.2. Applications of PCM

PCM are commercially used in multiple fields. Applications of PCM include:

- Thermal energy storage
- Conditioning of buildings
- Cooling of electrical engines
- Cooling food, wine, milk products, green houses
- Medical applications such as:
  - Transportation of blood
  - Operating tables,
  - Hot-cold therapies
- Waste heat recovery
- Off-peak power utilization: heating hot water and cooling
- Heat pump systems
- Passive storage in bioclimatic building/architecture
- Smoothing exothermic temperature peaks in chemical reactions
- Solar power plants
- Spacecraft thermal systems
- Thermal comfort in vehicles
- Thermal protection of electronic devices
- Thermal protection of food transport, hotel trade, ice-cream etc.
- Textiles used in clothing
- Computer cooling

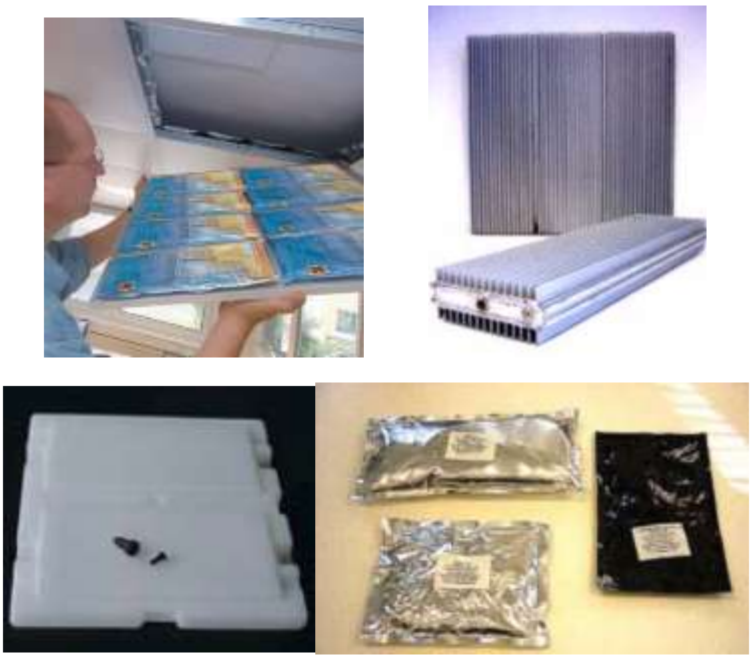

Figure: Different types and applications of PCM (Source: Papamanolis)

Moreover, researchers are currently investigating new applications classified as:

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- High temperature storage
- Domestic hot water tanks
- Active systems for heating
- Active systems for cooling
- Photovoltaic panels
- Passive building envelope or building component

5.3. Classification of PCM

The MESSIB report 'Design guide of integration of storage technologies' addresses in paragraph 'Organic and inorganic PCM' the following characteristiscs.

The working principle of phase change materials is based on the uptake and the release of heat energy during melting and crystallization, respectively. The most relevant material properties concerning the application are melting temperature, latent heat of fusion, and chemical stability.

PCM may be classified according to its chemical composition: Organic and Inorganic. The most common groups of PCM are listed below.

Organic PCM	Inorganic PCM
High aliphatic hydrocarbon Acid/esters or salts Alcohols Aromatic hydrocarbons Aromatic ketone Lactam Freon Multi-carbonated category Polymers	Crystalline hydrate Molten salts Metal or alloy Fatty acids

Table: Classificacion of different PCM as organic and inorganic.

The MESSIB report D1.1 'Identification of products and technologies energy related, relevant stakeholders and building classification according their different uses and typologies' addresses the following Organic and Inorganic PCM characteristics..

5.3.1. Organic

Organic Phase Change Materials can be Aliphatic or Other Organics. Users rarely specify the use of Organic PCMs. LatestTM can offer Organic PCMs in low temperature range. They are expensive and have average latent heat per unit volume and low density. Organic PCM with high molecular mass hydrocarbons are often referred as paraffins. Paraffins are the most common organic compound used as PCM for build. Sugar alcohols are other appropriate compound for PCM applications.

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Paraffin is a commonly used PCM, because it has relatively high latent heat (thermal energy storage densities of 150-200 J/kg or 150 MJ/m3), negligible subcooling, low cost and is stable, nontoxic, noncorrosive. Commercial paraffins have a wide range of melting temperatures. However, they have low thermal conductivity (~0.2 W/mK), which limits their applications.

Organic substances offer the possibility to adjust the melting temperature, and thus the operation temperature in the desired range. Additionally, they are chemically stable and have a low vapour pressure providing good cycle stability. However, the drawback of this material class is a lower storage density and a high fire load.

The main properties of organic PCM are summarised in the following table:

Organic PCM	
Advantages	No corrosive Low or no undercooling Physical and chemical stability Good thermal behaviour Adjustable transition zone
Disadvantages	Lower phase change enthalpy Low thermal conductivity Low melting point Inflammability Low density Volume change Highly volatile

Table: Advantages and disadvantages of organic PCM

In spite of the disadvantages of organic PCM, additives and additional layers can be implemented to materials in order to improve some characteristics of its behaviour. Such improvements may have an impact in higher thermal conductivity, lower inflammability…

5.3.2. Inorganic

Inorganic Phase Change Materials are generally Hydrated Salt based materials, due to its working temperatures being adapted to building heating. Moreover, fatty acids may also be appropriate for PCM applications in heating systems.

A disadvantage of most salt hydrates is the tendency to remain a liquid when the temperature is lowered, even below the freezing point. This effect is called 'supercooling'. A high degree of supercooling can even prevent the withdrawal of heat from the PCM. It is therefore important to reduce supercooling as much as possible.

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Hydrated salts are attractive materials for use in thermal energy storage due to their high volumetric storage density (~350 MJ/m^3), relatively high thermal conductivity (~0.5 W/mK), and moderate costs compared to paraffin waxes, with few exceptions.

The main limitation of salt hydrates is their chemical instability. Salt hydrates loose its capacity of latent heat with cycles. Besides salt hydrates tend to loose hydrate water.

Furthermore, some salts are chemically aggressive towards structural materials. Salt hydrates also have a relatively high degree of supercooling, which leads to the limitation of heat release.

The main properties of inorganic compounds are:

Inorganic PCM	
Advantages	Greater phase change enthalpy Higher energy storage density Higher thermal conductivity Non-flammable Low price
Disadvantages	Supercooling or subcooling Corrosive Phase separation Phase segregation, lack of thermal stability

Table: Advantages and disadvantages of inorganic PCM

There are some additives and encapsulation that may be used to improve the performance of Hydrated Salts characteristics: delaying the degradation of PCMs.

Hydrated salts have a number of hydrates and an anhydrous form leading to stratification of material and loss of latent heat recovery with time. Hydrated salts also have a sub-cooling tendency. Old generation PCM manufacturers managed to add performance-enhancing agents. These additives do help in delaying the degradation of PCMs for say 100 cycles or thereabout. However, impurities also promoted nucleation of undesirable hydrates leading to stratification. Experts on crystallography have managed to identify the "Preferred Crystal Nucleation" method. It consists of a "Cold Finger" that nucleates and promotes the growth of desired crystals and "Detoxification" or "Selective Elimination" whereby any impurity that promotes the growth of undesirable crystals is removed.

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5.3.3. Organic and inorganic PCM properties

Only PCM with melting temperatures of 16 to 30 ˚C could be considered for applications in buildings, and melting temperatures of 45 to 70 ˚C could be considered for storage tanks.

PCM compound	Melting temperature (˚C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/mK)	Density (kg/m3)
Inorganic	18-70	125-296	0.540-0.561	1447-1738
Inorganic eutetics	16-61	125-250	0.494-0.565	1515-1930
Inorganic mixtures	55-60	150	-	-
Organic	16-68	86-266	0.148-0.189	760-1126
Organic eutetics	53-67	123	0.130-0.136	-
Organic mixtures fatty acids	10-68	90-205	0.145-0.172	844-1033
Commercial on the market	22-70	108-259	~0.2	870-1480

Figure: Organic and Inorganic PCM material properties (Source: Wolfgang Streicher)

Although there are many materials studied as PCM, at the temperatures needed for most building applications, only paraffin, salt hydrates, fatty accids and sugar alcohols result appropriate.

5.4. Main properties

The most desirable properties for active energy storage that a PCM should accomplish are *(according to L. Cabeza):*

- A high energy density per unit of volume and weight
- A melting point in the practical range of operation
- A low vapour pressure (<1 bar) at the operational temperature
- A chemical stability and non-corrosiveness
- Not being hazardous, highly inflammable or poisonous
- Having a reproducible crystallisation without degradation
- Having a small supercooling degree and high rate of crystal growth
- Having a small volume variation during solidification
- A high thermal conductivity
- Abundant supply and at low cost

5.4.1. Hysteresis

The hysteresis phenomenon appears during cooling of materials. Hence, the phase change does not occur at the expected temperature. It does not depend on the solid phase presence in the surrounding.

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Supercooling and superheating are part of the several effects due to the material which cause real hysteresis. The most common in PCM is supercooling. Supercooling will lead to different results for heating and cooling; however, it is not a shift of the results to higher temperatures on heating and lower temperatures on cooling.

5.4.2. Convection

PCM materials have conductivity as the most important way of transferring thermal energy. PCM in solid phase have no possible heat transfer by convection, whereas they may have some convection heating transfer when they are at the liquid phase.

On the other hand, PCM in slurries, staying always in a liquefied medium, may also have some convection heating transfer.

5.4.3. Thermal Conductivity

The successful usage of PCMs depends mainly of the energy storage density, but also of the thermal power to charge and discharge the energy stored. One major inconvenience of LHS is the low heat transfer of the materials used as PCMs due to its low thermal conductivity and the negligible convection. These limit the power of charging and discharging from the thermal energy storage.

The thermal conductivity of PCM is relatively low, and can be improved by a matrix material such as graphite, copper or magnetite for example. The conductivity of pure PCM is of 0.2 W/mºC (paraffins) and 0.5 W/mºC (salt hydrates). If a matrix is added the thermal capacity may improve to up to 10-15 W/mºC.

Paraffin is a commonly used phase change material (PCM), because it has relatively high latent heat, low cost and is stable, nontoxic and noncorrosive. Its low thermal conductivity can be a drawback in high power applications. Several methods have been used to increase thermal conductivity of PCM previously. Most of these methods are based on dispersing high thermal conductivity particles, such as carbon, metals, graphite in PCM.

Magnetite, Fe3O4 is a highly magnetic and conductive material with thermal conductivity of 9.7 W.m-1.K-1. Thermal conductivity of paraffin at 46-48˚C is 0.21 W.m-1.K-1. Therefore with an attempt to enhance the thermal properties of paraffin, composite with nano magnetite has been prepared.

The results show that thermal conductivity of paraffin has been increased from 0.27 to 0.40 by about 50%, when 10% nano magnetite was used in the composite. This shows that nano magnetite has profound effect in increasing thermal conductivity of paraffin. Thermal diffusivity and thermal conductivity results are in accordance with each other. The thermal conductivity of the composites with higher nano magnetite will also be determined.

The cost of this composite is only 3% higher than pure paraffin. These results show that using nano magnetite to increase thermal conductivity of paraffin is an economic and effective method. However further studies on thermal cycling are necessary.

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Samples	Melting Range °C	Latent Heat (J/g)
Paraffin	52.7-62.1	119.9
Nano magnetite-paraffine composite	54.4-62.1	144.2

Figure: Differential scanning calorimetry results for paraffin and paraffin nano composites (Source: COST TU0802)

5.4.4. Volume change

The PCM expansion during the phase-change within a fixed volume of encapsulation needs to be analysed in detail to avoid breaking and damaging.

Usually, the PCM solid density is higher, like most organic and inorganic materials, whereas water is a notable exception. In practical terms, this change, which may be as large as about 10% in paraffins or salts, must be accommodated by a proper design of the system.

5.4.5. Lifetime

The lifetime of PCM is usually expressed in two ways:

- Lifetime in cycles (number of phase changes)
- Lifetime in years

The economical suitability and the lifetime in cycles are related. A cost-effective PCM depends on PCM phase changes number multiplied with the PCM energy content (kJ/kg), which should be at least equal to the PCM price (€/kJ).

PCM for commercial passive use in buildings (salt hydrates of Autarkis and paraffins of BASF) have been modified to resist more than 10.000 cycles of phase-change.

5.4.6. Temperatures

For Organic PCM, paraffins cover a wide range of melting temperatures for applications from -30ºC to 130ºC, whereas sugar alcohols have higher energy densities with temperatures from 90ºC to 180ºC (values of sugar alcohols melting temperatures).

On the other hand, for inorganic PCM, salt hydrates may go from 5ºC to temperatures higher than 130ºC.

5.4.7. Environment impact

The Volatile Organic Compound (VOC) impact of organic PCM such as paraffin is much higher than the VOC of inorganic PCM such as salt hydrate.

Material compatibility problems that are common among PCM are:

- Corrosion of metals in contact with inorganic PCM

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- Stability loss of plastics in contact with organic PCM
- Migration of liquid or gas through plastics that affect the performance of a contained organic or inorganic PCM and outside environment.

Another disadvantage of PCMs is its high Toxicity. This should be taken into account during its renovation and manipulation. A requirement of recyclability could be analysed.

Regarding emissions, it is important to compare the energy used to produce the PCM versus the energy saved during de lifetime of the PCM system. The total energy saved, is the energy stored multiplied by the number of PCM phases changed during its lifetime.

5.4.8. Maintenance

There is not direct maintenance to be done to PCM materials. In case of unexpected PCM damage, the PCM system parts should be replaced or repaired.

Auxiliary systems and components such as pumps, heat exchangers, vessels, valves and sensors should have a maintenance plan to prevent damages. The design of the integration of PCM should facilitate the maintenance work.

System maintenance requirements are not described in the references.

5.4.9. Energy density

A factor 2-3 higher storage capacity (kJ/kg) is possible when comparing PCMs to water as a storage media.

For Organic PCM, paraffins may have energy densities from 100 to 210 MJ/m^3, whereas sugar alcohols have melting temperatures available from 150 to 500 MJ/m^3.

On the other hand, for inorganic PCM, salt hydrates may go from 200 MJ/m^3 to 450 MJ/m^3.

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5.4.10. Cost

The main suppliers in the market of phase change heat and cold storage material include:

- BASF
- E. I. Du Pont De Nemours and Company,
- Honeywell International Inc.
- The Dow Chemical Company
- Cryopak
- Entropy Solutions
- Outlast Technologies
- Phase Change Energy Solutions
- AI Technology
- Croda International
- Henkel
- Laird
- Parker Chomerics
- PCM Products
- Phase Change Products
- Pluss Polymers
- Rgees
- Rubitherm Technologies

The price of PCM varies in the 0.3-10 €/kg range. The price of salt hydrates is usually low, in the order of 1 to 3 €/kg unless bought in pure form. Paraffins costs may be found as low as 1 €/kg.

Additional investment cost for auxiliary installations should be taken into account. The storage container and heat exchanger should be added.

In most cases, PCM can achieve competitive costs in case of high cycle number, reduction of the storage volume, its constant temperature and its energy grid independence. For instance, considering an energy price of 0.05 euro/kWh, a PCM price of 0.5 euro/kg becomes economic in case of storing a free energy total of 10 kWh/kg or 36 MJ/kg, which is equal to 200 cycles of a characteristic PCM energy content of 150 to 200 kJ/kg.

5.5. Active storage systems

In order to integrate PCM in an active storage system, PCM should be exchanging heat with water or another fluid through a heat exchanger or by direct contact.

In active systems PCM is found in storage tanks in the form of slurry, macro-encapsulated or micro-encapsulated.

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5.5.1. Types of encapsulation

In order to control the change of volume of PCM, reduce the risk of leakage and to increase heat exchangement and PCM is usually found encapsulated. Encapsulated PCM have a lower enthalpy than pure PCM and higher costs.

PCM are installed in thermal storage systems in the following forms:

- Macro-encapsulation
- Micro-encapsulation
- As a slurry in water tanks
- Molecular-encapsulation

5.5.1.1. Macro-encapsulation

Macro-encapsulation is the most widely habitual encapsulation storage technology. It was also the first encapsulation to be developed. The most common approach is to use a plastic module, which is chemically neutral with respect to both the phase change material and the heat transfer fluid. Metal may also be used for encapsulation.

This technology has the advantage of having a high energy density and low prices, although having the disadvantage to let the container leak, if perforated.

PCM macro-encapsulation PCM may be stored in Balls or in tubes with a small diameter and large height. The modules typically have a diameter of some centimetres.

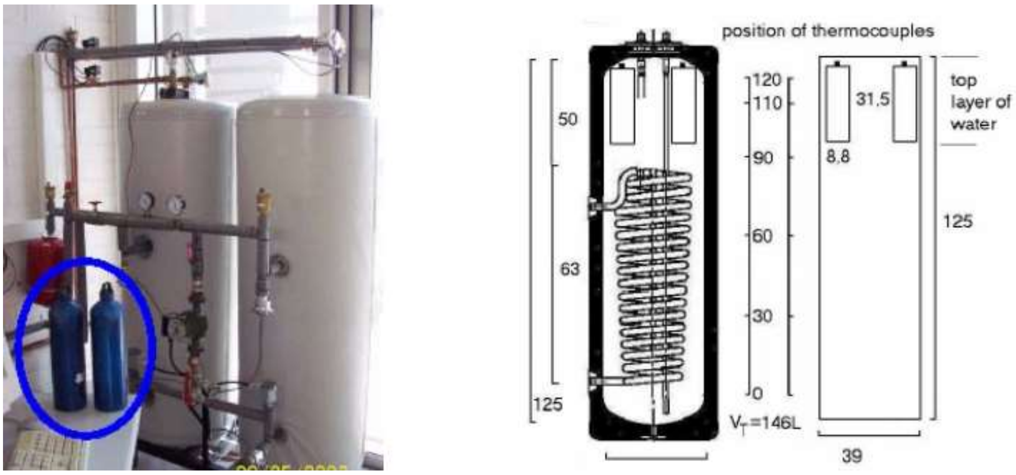

Figure: PCM modules included in domestic hot water tanks

5.5.1.2. Micro-encapsulation

This is a relatively new technique in which the PCM is encapsulated in a small shell of polymer materials with a diameter of some micrometres (in the moment only for paraffins).

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Micro-encapsulation shows no problem of volume variation or leakage. Any damage to a micro encapsulated PCM, may release only a very small amount of container. Micro-encapsulation has higher costs and lower energy densities.

The micro encapsultaion is technically feasible today only for organic materials.

Figure: Micrencapsulated PCM commercialized by BASF

5.5.1.3. Slurries

PCM outmatch conventional water storages in many applications. But using pure PCMs the usable heat exchange mechanisms are reduced to conductive heat exchange, which is significantly lower than convective heat exchange of fluid based media.

Phase Change Slurries (PCS) can combine the advantages of both, water with its good heat exchange behaviour, and PCM. Another advantage is that the PCS stays liquid, even when the PCM is frozen.

For high temperature differences of more than 20 K and especially with low concentrations of PCM the storage capacity is not much better than for water. Therefore PCM slurries should potentially be used in systems that are operated with low temperature differences. The concentration of slurries should be as high as possible.

MESSIB Project D2.6 describes an experiment in a storage tank containing 30% of capsules in water. Besides the enhancement of some properties, by the end of the experiment, it was detected that the slurry had been separated within the storage tank and the encapsulated PCM located at the top. Afterwards, there were carried out different tests with additives, but as the use of additives increases, it also rises the viscosity and consequently this has a negative influence on the power consumption of pumps and performance of heat exchangers. Further investigations are required.

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Figure: PCM slurry

5.5.1.4. Molecular-encapsulation

It exists also a new technology developed by DuPont which is molecular-encapsulation. It allows a very high concentration of PCM within a polymer compound. The polymer molecules have been designed to 'connect' to the PCM molecules, creating therefore a homogenous compound. Molecular-encapsulation allows drilling and cutting through the material without any PCM leakage. It is usually applied as a construction material in passive systems.

5.5.2. Storage tanks

There is no special external difference between storage water tanks and PCM tanks. As in water tanks insulation and volume available will be big issues.

PCM storage tanks will be less stratified tank water tanks, they will have to have an exchange method that internally guarantees the maximum energy density and energy power.

Macro-encapsulation in PCM tanks can be found horizontally or vertically. If some degree of stratification should be needed, PCM modules may be installed at different levels.

In tanks with PCM as a slurry, there should be installed an internal tubular heat exchanger filled with another fluid.

Some suppliers of PCM tanks are:

- Latentspeicher (PowerTank)
- LaTherm (Germany)
- PowerTank (Latentspeicher) (Germany)
- EPS, PCM Products (UK)

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5.6. Analysis of Buffer/daily storage

The characteristics of PCM may be suitable for the particular case of buffer/daily storage. For this particular case, the most appropriate LHS system will be analysed.

A temperature of storage around 75°C is considered for the analysis. In this range of temperature, paraffins are suggested as an appropriate PCM.

The commercially available products in the temperature range are as follows:

Manufacturer	Product	Temperature	Heat kJ/kg
RGEES	savEnrg	65°C	210
PCM Products Ltd	PCM A70	70°C	173
PureTemp	PureTemp 68	68°C	213
Rubitherm	RT70HC	70°C	260

The following graph illustrates the typical performance of these types of materials in that they change phase across a range of temperatures.

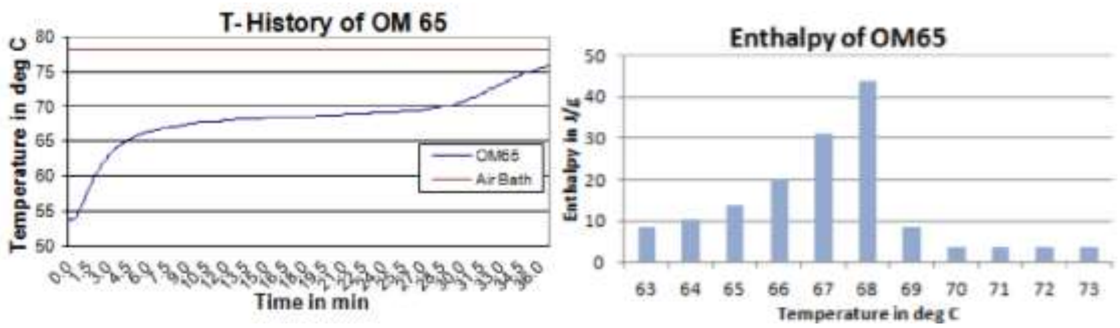

Chart: savEnrg 65°C PCM performance

Research materials in the relevant temperature ranges include:

Material	Temperature °C	Heat of Fusion (kJ/kg)
$Na_2B_4O_7.10H_2O$	68.1	
$Na_3PO_4.12H_2O$	69.0	
$Na_2P_2O_7.10H_2O$	70	184
$Ba(OH]_2.8H_2O$	78	266
$(NH_4)Al(SO_4)_2.12H_2O$	95	269
$MgCl_2.6H_2O$	117	169
$Mg(NO_3)_2.6H_2O$	89.3	150

Table: available PCM properties (Source: University of Ulster)

The most suitable product is Rubitherm RT70HC as a commercially available PCM. Its properties are as follows:

- Melting Temperature 69-71°C

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-	Congealing Temperature	71-69°C
-	Heat Storage Capacity	260 kJ/kg ±7.5%
-	Combination of latent and sensible heat in a temperature range of °C to °C	64 Wh/kg
-	Specific Heat Capacity	2 kJ/kg.K
-	Density of solid (@ 15°C)	0.88 kg/litre
-	Density of liquid (@ 80°C)	0.77 kg/litre
-	Heat Conductivity (both phases)	0.2 W·m/K
-	Volume expansion	12.5%
-	Flash point	227°C
-	Maximum Operation Temperature	100°C

PCM Rubitherm RT70HC material cost would be around 2€/kg.

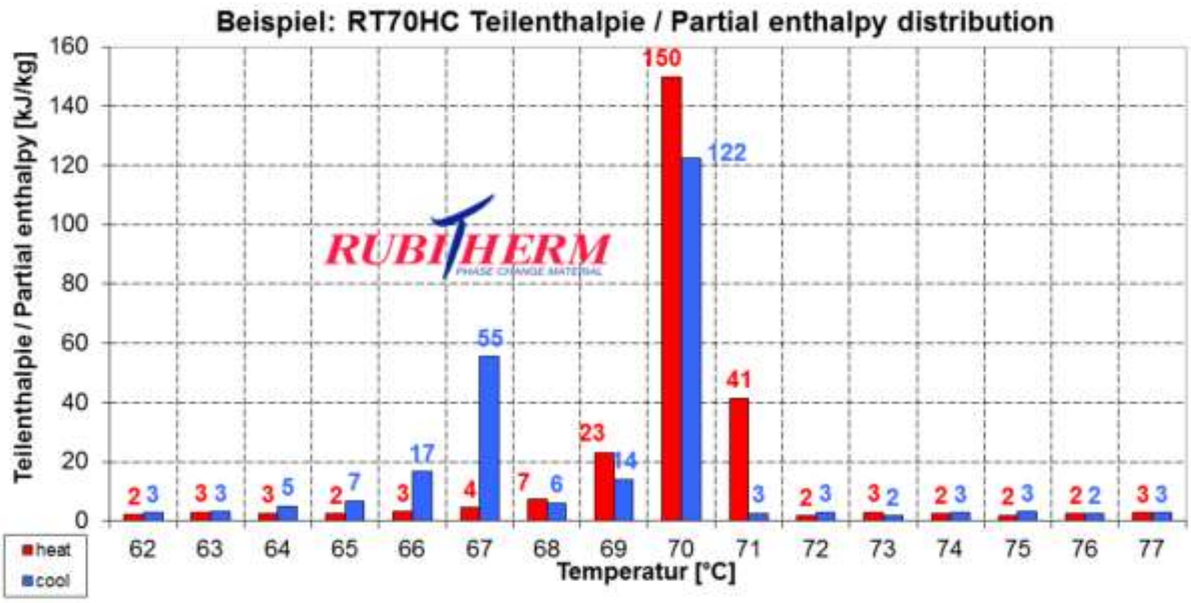

Chart: RT70HT Performance Graph

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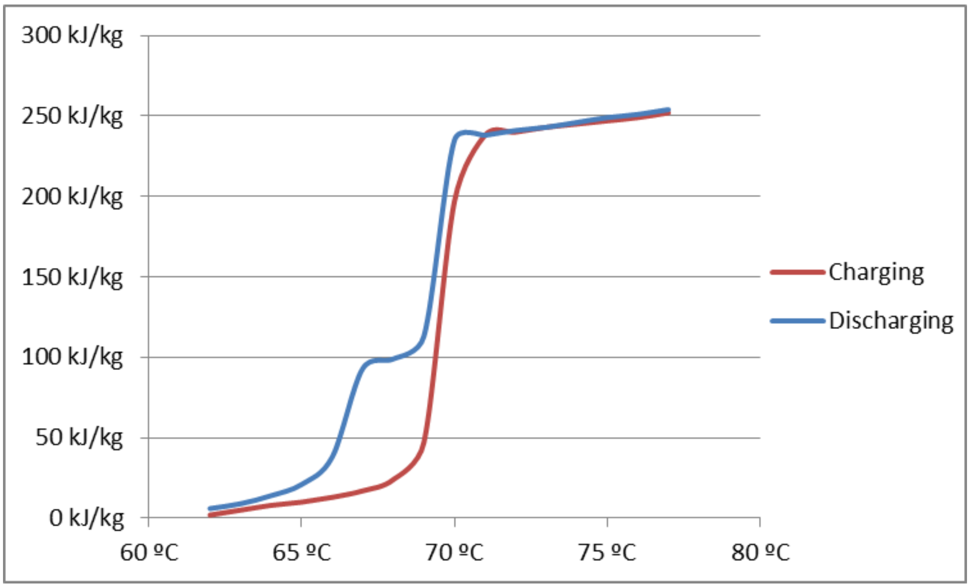

Chart: RT70HT Charging and Discharging temperature and entalphy variation

(Source: adapted from Rubitherm)

A number of PCM tank designs may be suitable base on encapsulated or non-encapsulated solutions. Some examples include a Crystopia design, Frazzica et al (2014), Ulster University's design (Huang et al, 2011), and the related Calmac design and the ZAE BAYERN capillary tube option. These are summarised in the following diagram.

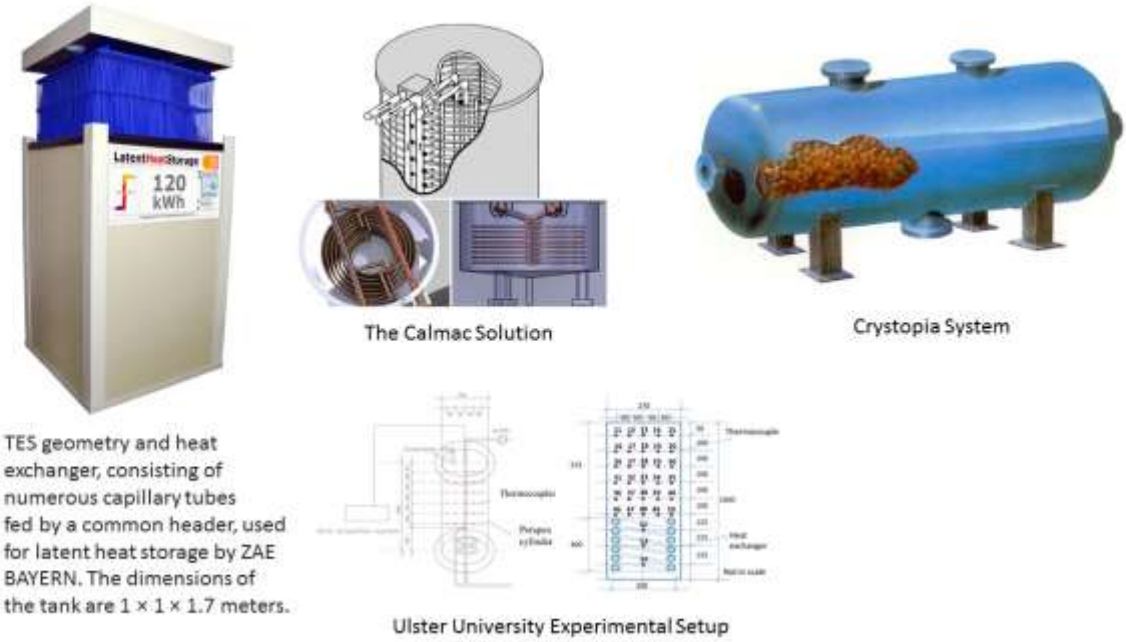

Figure: Summary of Likely Designs (Source Ulster University)

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5.7. Advantages /disadvantages of PCM

Advantages and disadvantages of PCM in front of sensible and latent energy storage are listed:

Advantages	Disadvantages
Higher energy density Stable storage temperature Suitable for a wide range of temperatures Suitable for small operational temperature range Easily embedded in building construction material relatively constant temperature during charging and discharging As a passive system, it doesn't require a direct control system	High cost No stratification Temperature hysteresis High environ risk (Inflammability, toxicity and corrosive) Deterioration Low heat transfer limited experience with long-term operation

5.8. Table Summary

Material	Energy density (kWh/m3)	Cost (€/t)	Heating Temperatures (ºC)	Density (kg/m3)	Heat conductivity (W/mK)
Salt hydrates	14 – 125	0.3-3	20-130	1,300	0.5
Paraffins	28-56	1-10	20-130	750-830	0.2

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6. Thermo-chemical Materials Energy Storage

6.1. Definition

Thermo-chemical materials (TCM) are materials that can store thermal energy by a reversible endothermic/exothermic process. The process absorbs energy in one direction and releases energy in the reverse direction. TCM reactions require at least the combination of two substances.

In the thermal energy absorbing reaction, the material is converted chemically into two components, which can be stored separately. In the reverse reaction the two components are combined together and the material is formed, releasing thermal energy in the reaction.

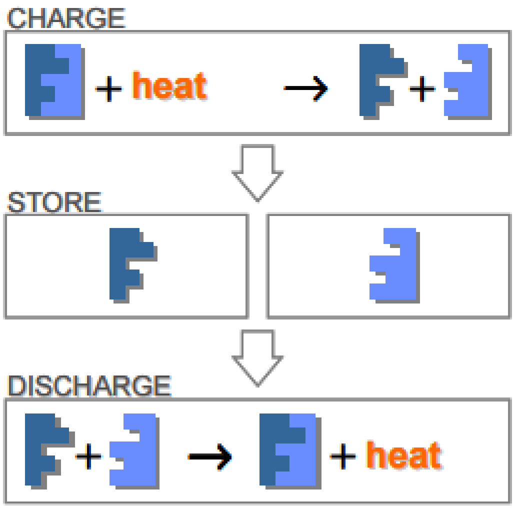

Figure: Thermochemical energy charge and discharge

For the moment the Technology Readiness Level (TRL) of TCM systems is lower, compared to alternatives such as PCM systems for example. Most of the materials are being investigated or developed in Research Centeres and Universities.

6.2. Classification

There are three reactions that are encompassed as TCM reactions:

- Absorption: In which molecules of the absorbate material are incorporated into the bulk of the absorbent.
- Adsorption: In which molecules of the adsorbate material are adhered to the surface of the adsorbent material.
- Chemical reactions: uses gas reaction with solid reactant. These reactions have higher energy density than sorption process, but experiment volume change in solid reactant which could be a source of material degradation.

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6.3. Material characteristics

Two main groups of TCM materials are currently being studied and developed as seasonal storage systems:

- Zeolites: is a group of crystalline aluminosilicates and oxygen material, which has a capacity of molecularly adsorbing water. There are forty natural and over one hundred synthetic existing zeolites.
- Salt hydrates: is a group of salt crystal matrix that has a high capacity to adsorpt water due to its high internal surface. Most common salts include magnesium sulphate, magnesium chloride, sodium sulphate and calcium salts.

Silica gel is another type of material that has been widely studied as a TCM material for energy storage.

Figure: Examples of zeolite in different shapes and sizes: beads, pellets and extruded brick(SAIC)

In this section the material characteristics influencing the selection of a TCM material are presented.

6.3.1. Stability

Stability in time is a problem in the use of salt hydrates as storage systems. The current types of salt hydrates are difficult to keep stable over a longer period. Research is being done to improve the stability of salt hydrates.

This issue plays a much lesser extent by zeolites, although some attention has to be made when choosing zeolites in storage systems.

6.3.2. Corrosiveness

Corrosiveness is another important issue concerning salt hydrates. Metals in contact with salt hydrates have to be studied and selected specifically for each case.

On the other hand, zeolites don't present important corrosion problems.

6.3.3. Energy density

A factor 2-3 higher energy density is possible when comparing PCMs to water as a storage media, and 5-6 comparing TCM to water.

Energy density for different types of salt hydrates operating with low temperatures (25-150ºC) is 0.4-2.8 GJ/m3 (140 – 780 kWh/m^3). On the other hand zeolites have an energy

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density of around 55-250 kWh/m[3]. These energy densities include just the material, they don't include heat exchangers and separate vessels, that could reduce densities by 3 times.

Some prototype salt hydrates materials investigated are listed below:

Salt hydrate	Chemical Formula	Theoretical crystal energy density (GJ/m3)
Magnesium sulphate Heptahydrate	$MgSO_4 \cdot 7H_2O$	2.3
Aluminium sulphate Octadecahydrate	$Al_2(SO_4)_3 \cdot 18H_2O$	2.2
Potassium aluminium sulfate Dodecahydrate	$KAl(SO_4)_3 \cdot 12H_2O$	1.5
Sodium Sulphate Decahydrate	$Na_2SO_4 \cdot 10H_2O$	2.4
Magnesium Chloride Hexahydrate	$MgCl_2 \cdot 6H_2O$	1.9
Calcium Chloride Dihydrate	$CaCl_2 \cdot 2H_2O$	1.6
Sodium Sulphide Pentahydrate	$Na_2S \cdot 5H_2O$	2.7
Strontium Bromide Hexahydrate	$SrBr_2 \cdot 6H_2O$	2

Table: Theoretical energy density calculated for salt hydrates materials reacting in the temperature range of SSHS (25- 150°C) under low (H2O) conditions (Ferchaud)

6.3.4. Cost

TCM materials have a cost that ranges from 8 to 100 €/kWh. In general salt hydrates are much cheaper than zeolites.

Additionally, according to developers and researchers the cost of the global system would be at least the double of the material cost.

The cost of the prototype salt hydrates materials investigated is:

Salt hydrate	Chemical Formula	Cost (€/t)
Magnesium sulphate Heptahydrate	$MgSO_4 \cdot 7H_2O$	50-100
Aluminium sulphate Octadecahydrate	$Al_2(SO_4)_3 \cdot 18H_2O$	100-150
Potassium aluminium sulfate Dodecahydrate	$KAl(SO_4)_3 \cdot 12H_2O$	200-400
Sodium Sulphate Decahydrate	$Na_2SO_4 \cdot 10H_2O$	75-100
Magnesium Chloride Hexahydrate	$MgCl_2 \cdot 6H_2O$	50-100
Calcium Chloride Dihydrate	$CaCl_2 \cdot 2H_2O$	75-150
Sodium Sulphide Pentahydrate	$Na_2S \cdot 5H_2O$	300-500
Strontium Bromide Hexahydrate	$SrBr_2 \cdot 6H_2O$	2,400

Table: Cost estimation from web providers calculated for salt hydrates materials reacting in the temperature range of SSHS (25- 150°C) under low (H2O) conditions (Ferchaud)

Materials cost could be reduced in the next years by improving technology and by economies of scale.

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6.3.5. Temperatures

The temperatures range of 25ºC to 150ºC is under investigation for zeolites and salt hydrates for de desorption and adsorption processes.

TCM show a more stable temperature than PCM when discharging and charging heat to the system.

The EINSTEIN D1.2 report 'EINSTEIN Technology assessment of HVAC and DHW systems in existing buildings' addresses that an important parameter determining a successful application of STES systems is the supply temperature of the heating system. In water based systems, storage at high temperatures leads to higher thermal losses. Advanced systems, such as the Thermo Chemical Storage (TCS) do not suffer from thermal losses during storage. The supply temperature of the heating system is still important because TCS systems are generally tailored to a specific temperature range.

Another parameter of interest is the power of heat supply, in particular for Thermo Chemical Storage. For some types of TCS, thermal power may be limited and the system has to be used in combination with a water based storage vessel.

6.3.6. Temperature hysteresis

According to *Ferchaud*, several salt hydrates show a temperature hysteresis between the dehydration and hydration around the equilibrium conditions of the materials. In the literature, the hysteresis of reaction is assumed to result from physical and mechanical effects occurring in the material (self-cooling, activation process). This temperature hysteresis lowers the effective reaction temperature on hydration, which can lead to a reduced temperature lift.

6.4. Advantages/disadvantages of TCM

Advantages and disadvantages of TCM in front of sensible and latent energy storage are listed:

Advantages	Disadvantages
High energy density Stable storage temperature Suitable for a wide range of temperatures No thermal losses during storage	High cost No stratification possible Low commercial development Corrosive and unstable Temperature Hysteresis

Table: Advantages and disadvantages of TCM

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6.5. Table summary

Material	Energy density (kWh/m3)	Cost (€/t)	Temperatures (ºC)
Salt hydrates	140 – 780	50-500	20-150
Zeolites	55-250	-	20-150

7. Summary

In order to help the selection of the TES a review of the existent technologies has been done. Advantages and disadvantages of each technology have been described, data has been analysed and treated to summarize a comparison given the same conditions of thermal power and temperatures. A ratio between overall costs (investment, operational and maintenance costs) and energy capacity has been considered.

The three existent big technologies of storage have the following characteristics:

- **Sensible Heat Storage (SHS)** technologies are the most developed, known and economical technology, they are the most suitable for stratified systems such as STES storage systems and systems with a wide range of working temperatures.
- **Latent Heat Storage (LHS)** technologies are competitive in systems that require a stable temperature and in systems with minor working temperature differences. They are less competitive in systems with a wider range of working temperatures where studies have shown small or no energy density improvement compared to SHS water systems.
- **Thermo-Chemical Materials Storage (TCMS)** technologies are not yet commercially developed. They are more competitive in higher temperature. Provided the conventional thermal panels or PVT panels production temperatures, it is a technology not suitable for these systems.

The main features of the different technologies systems are summarized in the two following tables. The first table summarizes the most important parameters.

The cost (€/kWh) in the table has considered investment costs, operation costs and maintenance costs.

The data will be used in the charts and programs designed to help the decision of the most valuable heating storage system.

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TES Technology		Energy density (kWht/t)	Energy density (kWht/m3)	Power (kW)	Efficiency (%)	Storage duration (h, d, m)	Cost (€/kWh)
SHS		5-80		1-10,000	50-90	d/m	0.08 - 10
Systems	TTES	60-80	60-80	1-10,000	50-90	d/m	0.08 - 0.1
	PTES	60-80	60-80	1-10,000	50-90	d/m	0.08 - 0.1
	GWTES	20-50	30-50				
	ATES	5-10	15-30	500-10,000	50-90	d/m	0.16 - 0.4
	BTES	5-10	30-40	100-5,000	50-90	d/m	0.16 - 0.4
LHS		10-150		1-1,000	75-90	h/m	10 - 50
Materials	Paraffins	30-75	28-56			h/m	
	Salt hydrates	10-100	14-125			h/m	
TCM		55-780		10-1,000	75-100	h/d	8 - 100
Materials	Salt hydrates	140-780				h/d	
	Zeolites	55-250				h/d	

Table: Parameters of Thermal Energy Storage Systems (Adapted from IRENA and Gas Natural)

The second table summarizes the advantages and disadvantages of the three main technologies that have been previously described in the current document.

	SHS	LHS	TCM
Cost	+	~	-
Energy Density	-	~	+
Stratification	~	-	-
Range of temperatures	~	+	+
Temperature Stability	-	+	+
Environ risks	+	-	-
Heat transfer	+	-	-
Deterioration	+	-	-
Temperature hysteresis	+	-	-
Commercial Development	+	~	-

+ high/ ~ moderate / - low

Table: Advantages and disadvantages of Thermal Energy Storage Systems (Source: Veolia)

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8. Conclusions

Thermal Energy Storage is a key component in a system with thermal/PVT panels and heat pumps that require an active storage system.

Before choosing the most suitable storage, it is required to identify some important parameters of the projected system: production temperatures, heating temperatures, storage capacity, thermal power, storage duration, space availability and energy costs.

The energy costs savings of a thermal storage should compensate the investment, maintenance and operational cost

In the thermal/PVT panels and heat pump installations, two types of thermal storage are being projected: a Buffer/Daily Storage and a Seasonal Thermal Energy Storage (STES). Thermal/PVT panels will be installed upstream of STES storage, while heat pumps will be connected downstream of STES storage and upstream of buffer/daily storage. Heat pumps, in order to have an adequate performance, need to have a stable input temperature and flow from STES storage (evaporator side) and a stable input temperature and flow from Buffer/daily storage (condenser side).

Seasonal Thermal Energy Storage (STES)

STES should be dimensioned to be able to store all the excess energy of the summer period.

In the specific case of PVT panels STES will have low output temperatures, thus temperature storage will be low. Temperatures of storage will even be lower if a heat exchanger has to be installed between PVT and STES. In both cases STES will have low energy density and a large volume.

On the other hand, a wider range of temperatures may be produced with thermal solar panels, so STES may have higher temperatures of storage to up to 90ºC.

In order to increase thermal/PVT performance, inlet thermal/PVT temperatures have to be the lowest possible. For this reason, STES is recommended to be well stratified.

The best adapted technology for STES are Sensible Heat Storage. PTES and TTES have the advantage of permitting a good stratification, have a high efficiency (if well-isolated) and low temperature hysteresis between charging and discharging. Volume occupation is the biggest disadvantage. Adding Gravel in PTES of TTES decreases the performance of the system, reducing energy density and stratification.

ATES and BTES have no volume occupation disadvantages. Its most notable disadvantages are the efficiency, the temperature limitation (does not apply for thermal/PVT panels), stratification and environ affectation. In both cases boreholes have to be designed to permit the highest possible stratification.

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Another possibility of reducing the storage volume in STES could be the installation of Phase-Change Material (PCM) in the upper parts of the water tanks. PCM selection should be adapted to charging and discharging temperatures. PCM installation would increase storage cost. Thermochemical Materials (TCM) are not recommended for its current low commercial use, neither for buffer/daily storage.

Buffer/Daily storage

Electricity prices, heat pump investment and buffer storage investment have to be compared before considering to convert a buffer storage into a daily storage.

The dimension of a buffer storage with no need of daily storage has to be able to store all the energy production of the heat pump during at least 15 minutes, in order to avoid more than 4 starts per hour of the compressor.

On the other hand, daily storage should be able to store the average energy daily demand without considering energy demand during the lowest electricity daily periods.

The thermal charging power of buffer/daily storage should be at least the heat pump condensation power, whereas the thermal discharging power should fit the power demand.

The temperature of storage of buffer/daily storage should be in accordance with the installation and required temperatures of the existing heating and DHW demand. In the particular case of PCM/TCM storage a heat exchanger has to be installed, thus its temperature difference between primary/secondary materials implies a higher temperature energy storage.

As in STES storage, for buffer/daily storage, the most used storage is water tanks, due mainly to cost, stratification properties and low temperature hysteresis between charging and discharging. Water tanks' he most notable disadvantages are the lowest temperature stability and the low energy density.

PCM are recommended in buffer/daily storage systems where heat pump requires a stable temperature. PCM increases energy density in small temperature differences and stabilizes temperature of storage. PCM tank investment cost will be higher than water tanks.

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9. Acronyms

AHU: Air Handling Unit

ATES: Aquifer Thermal Energy Storage

BTES: Borehole Thermal Energy Storage

CHP: Combined Heat and Power

COP: Coefficient of Performance

DHW: Domestic Hot Water

FCU: Fan-coil unit

GWTES: Gravel-Water Thermal Energy Storage

HDD: Heating Degree-Days

LHS: Latent Heat Storage

PCM: Phase-Change Material

PCS: Phase-Change Slurries

PTES: Pit Thermal Energy Storage

PVT: Photovoltaic-Thermal

SHS: Sensible Heat Storage

SSHS: Seasonal Sensible Heat Storage

STES: Seasonal Thermal Energy Storage

TCM: Thermo-Chemical Materials

TCMS: Thermo-chemical Materials Storage

TES: Thermal Energy Storage

TTES: Tank Thermal Energy Storage

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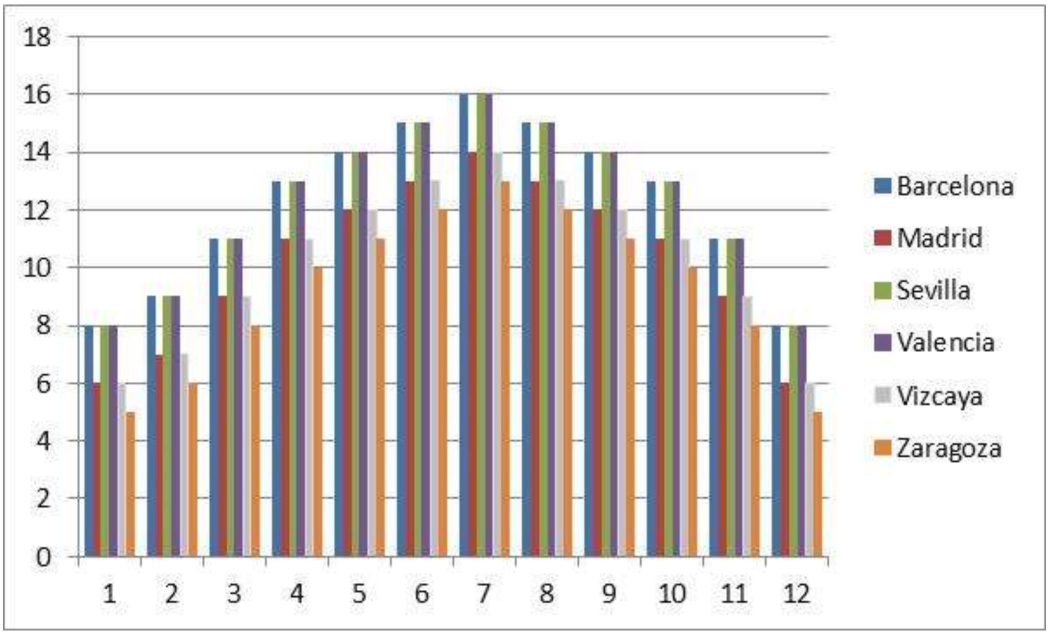
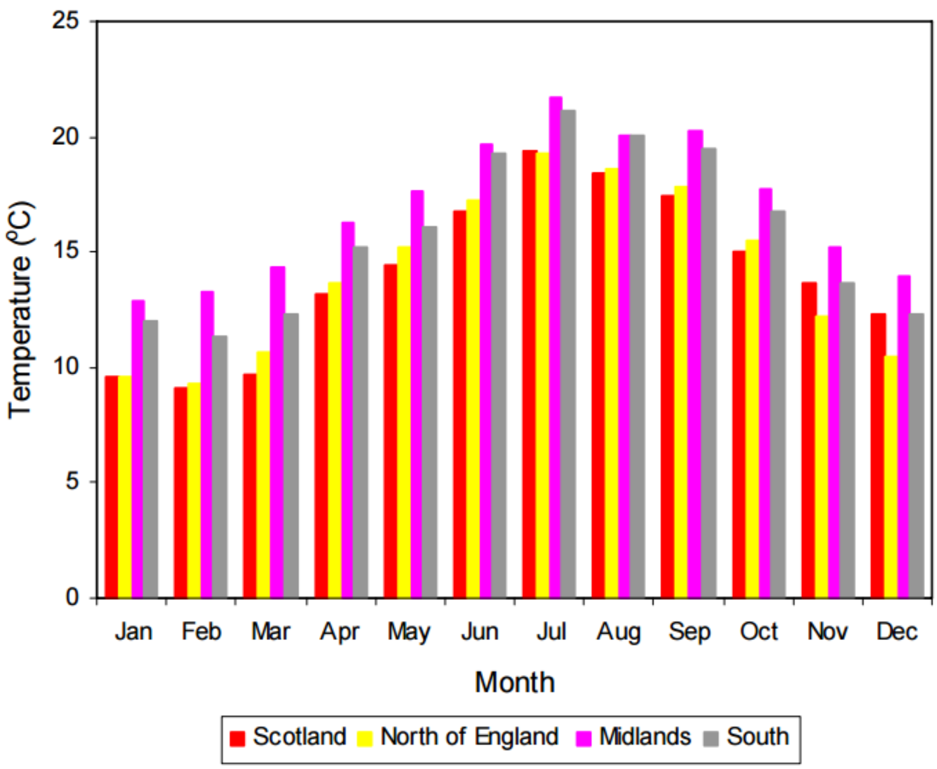
A. Appendix 1: Cold Water Network Temperatures

A.1. Spain



Average temperature of cold water network, in ºC (Source: CENSOLAR)

A.2. United Kingdom



Regional variation of cold water inlet temperature (Source: Energy Saving Trust)

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