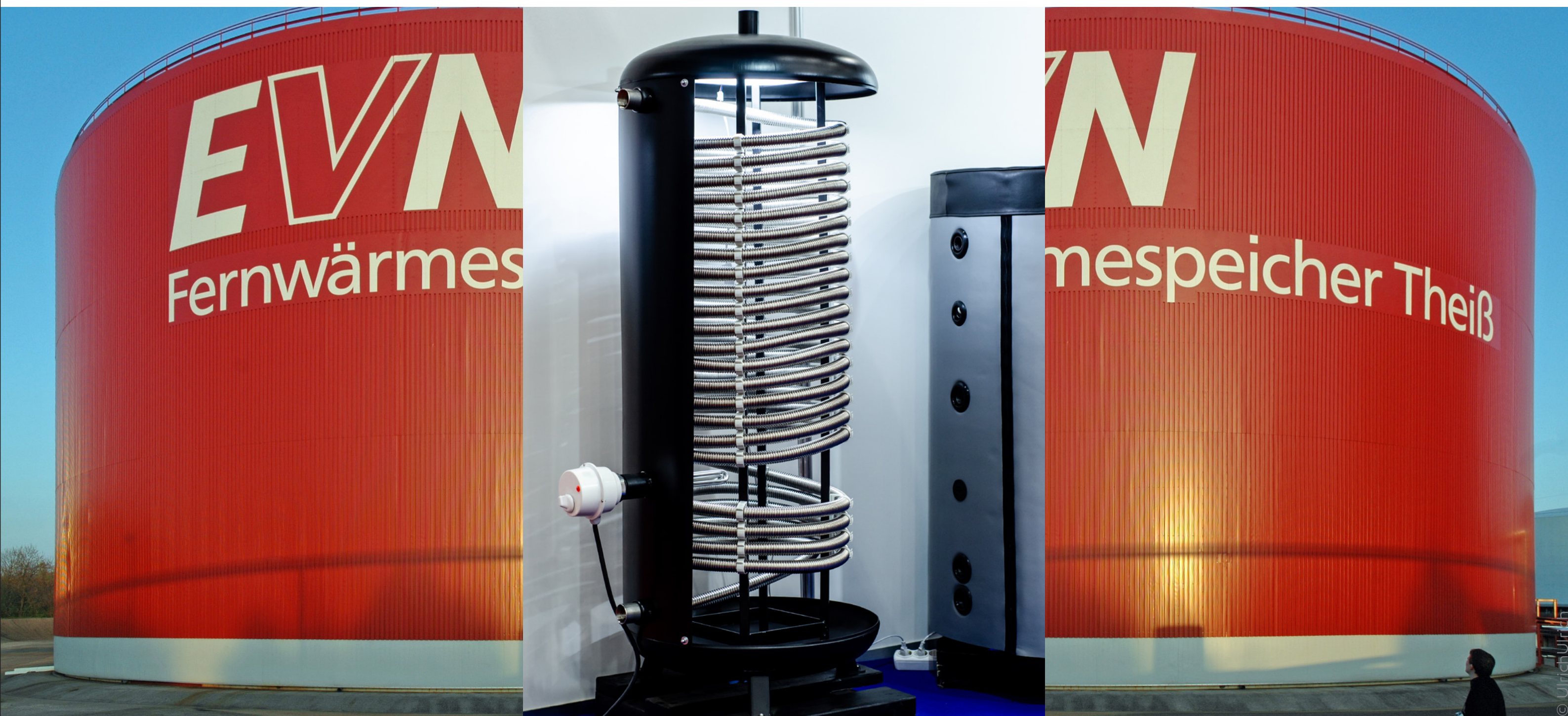
INSTITUT INTERNATIONAL DU FROID
INTERNATIONAL INSTITUTE OF REFRIGERATION

THERMAL ENERGY STORAGE SYSTEMS



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“A well-designed TES system can reduce energy consumption through more efficient equipment operation and lower investment costs, reducing the equipment capacity.”

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Thermal energy storage systems

Energy demand is seldom steady. Its variation often requires over-sizing of energy conversion systems to satisfy the peaks. On the other hand, energy supply may not be steady, which is typically the case for renewable energies, such as solar or wind energy.

Energy storage can mitigate or even solve the above problems. This note deals with Thermal *Energy Storage* (TES) systems. In this category also, cold thermal storage systems must be included. These systems can be widely implemented in building services, such as ambient and domestic hot water heating, air conditioning, and in many solar energy applications.

Thermal storage can be *sensible*, i.e. based on a temperature difference, or latent, i.e. based on the phase change of a substance; if sensible it can be done with a liquid or a solid. It can be sized to meet demand over different time periods (hours, days, weeks, etc.).

A well-designed TES system *can reduce energy consumption* through more efficient equipment operation and *lower investment costs*, reducing the equipment capacity. The storage shall be properly designed and managed, for example by carefully considering stratification issues in liquid systems and heat transfer for latent storage.

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Introduction

A simple computation illustrates the usefulness of a *Thermal Energy Storage* (TES) system. If you take a shower with water at 40°C and the mains at 10-15°C, the instantaneous heating of this water would require about 20-25 kW heating capacity. A 50-litre tank could provide water for a couple of showers, and even a third if the first two are reasonable, using less than 1 kW of capacity. In a similar way, a pair of solar collectors provides domestic hot water for a family from the impinging solar energy during a whole day. Technical developments in TES systems extend the possible applications to many other different fields.

The above examples regard *heat* storage. Cold storage is also possible and useful.

Energy demand is typically variable. A plant design without storage obliges to size the components depending on demand peaks. This kind of over-sizing increases investment costs and usually reduces efficiency in normal operations, as capacity modulation frequently penalises performance. Moreover, if the energy converter of the plant is supplied on a contract basis, a higher engaged power implies higher costs, especially for electricity. This is only one of the main advantages. Consider in figure 1 the typical daily cooling load of a shopping centre. No demand at night and a load that increases during daytime hours to 480 kW. The horizontal line at 160 kW is selected in order to produce the same cooling of the daily load, operating the chillers continuously: the cold stored during the night allows to satisfy the increasing diurnal demand. The benefits are manifold: lower investment cost for the chillers, higher efficiency for steady operation and a cheaper contract with electricity suppliers. The design can be improved by reducing electricity demand from the chillers at peak hours, thereby cancelling the demand at these expensive periods.

The above example indicates the possible contribution of TES systems to *demand-side management* [1]. In fact, widespread use of TES could *shift electrical loads from on-peak to off-peak hours or reduce the mismatch* between availability of renewable energy and demand.

Any intermittent energy source can be leveraged thanks to a storage system. Solar energy is a typical example. Other lesser-known applications are in *industrial batch processes.* A batch process is a process that has a beginning and an end, in short it is not continuous: spaghetti cooking is a batch process. Many industrial processes are of a batch type, and require thermal treatments, e.g. yarn dyeing, food or beverage processing. Only a suitable TES allows energy to be recovered from one batch process and applied to the following.

Cogeneration offers another possible profitable TES application as electricity and heat demand seldom matches the cogenerated electricity and heat. A TES *decouples* the two energy forms, so that the heat can be used later than its development.

The above examples require only a few hours of storage capacity. Technological developments are oriented to extend the storage period to weeks or even a whole year, e.g. from summer to winter and vice versa, thus achieving seasonal energy storage [2].

Many possibilities exist to achieve TES [3]; they are summarised by the tree charts in figure 2. TES can be either *sensible* or *latent*[1] . A sensible TES is obtained by raising or lowering the temperature of a substance or material. A latent TES is based on a phase change of a substance, a process which takes place with no or very little temperature difference, so that it can be considered as practically isothermal. The most common phase change used in TES is from solid to liquid or vice versa. Water is the most common substance in sensible storage, but also in latent providing cold storage based on the ice-liquid phase change.

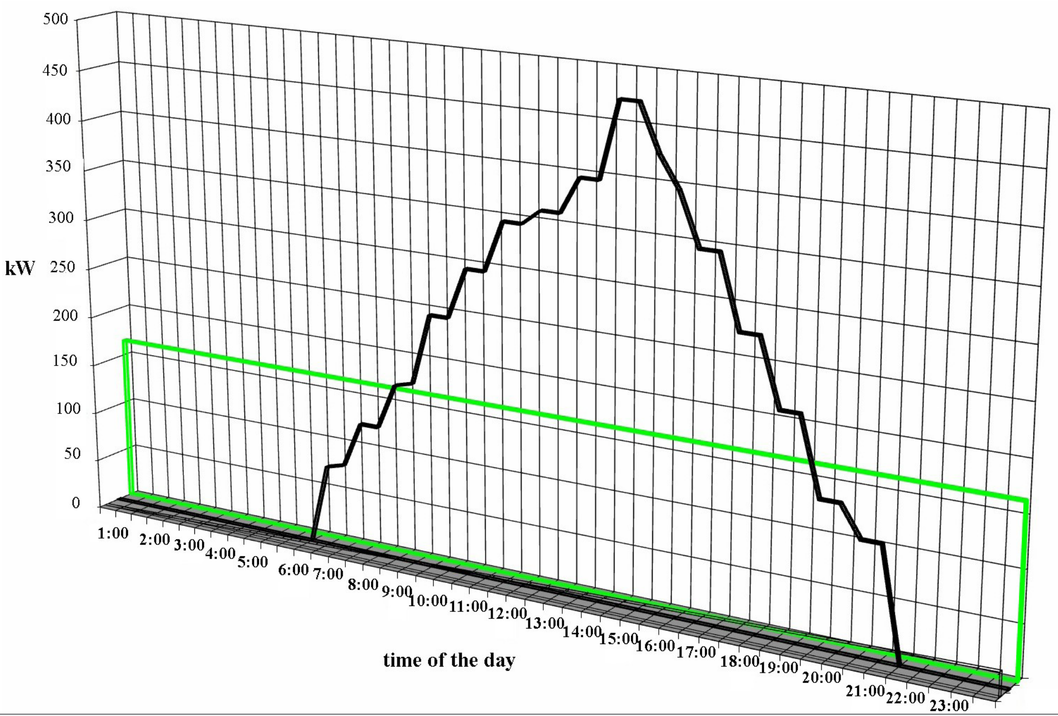
The thermal capacity of solids like rocks, pebbles, concrete is the basis for a family of sensible storages with pros and cons with respect to liquid systems. Finally, an aquifer is normally a natural storage where the temperature difference involves both water and rocks.

Many different technologies are used within each TES family to promote stratification in liquid-based systems or to enhance the heat transfer in solid-based ones. Latent TES, so far presented only for liquid-water ice phase change, can resort to a wide variety of substances, called *Phase Change Materials* (PCM), characterised by different phase change temperatures and heat of fusion. A description of the most common systems and their application will now be proposed.

[1] Another possible technology for TES is based on a reversible chemical reaction between two substances (chemical storage) with exothermic synthesis process and endothermic decomposition. However, the development of this technology is mainly at the level of theoretical and laboratory research [3].

Figure 1:

A possible daily cooling load of a shopping centre represented together with the constant cooling capacity that can satisfy the load by a suitable cold TES



Sensible TES

Basically, a sensible TES consists of a liquid or solid storage medium, a container and devices for charging or discharging the storage. The storage medium does not undergo a phase change. Instead, its temperature is changed and the storage energy capacity *Q* (J) is proportional to the mass of the storage *m* (kg), the specific heat capacity of the medium c_p ($Jkg^{-1}K^{-1}$) and the difference between the final storage temperature T_f (K) and the lowest (or highest in case of cold storage) available useful temperature T_i (K). The mass can be expressed as the product of the density of the medium c_p (kgm^{-3}) and the volume of the storage *V* (m^3) :

$$Q = mc_p(T_f - T_i) = \rho V c_p(T_f - T_i)$$

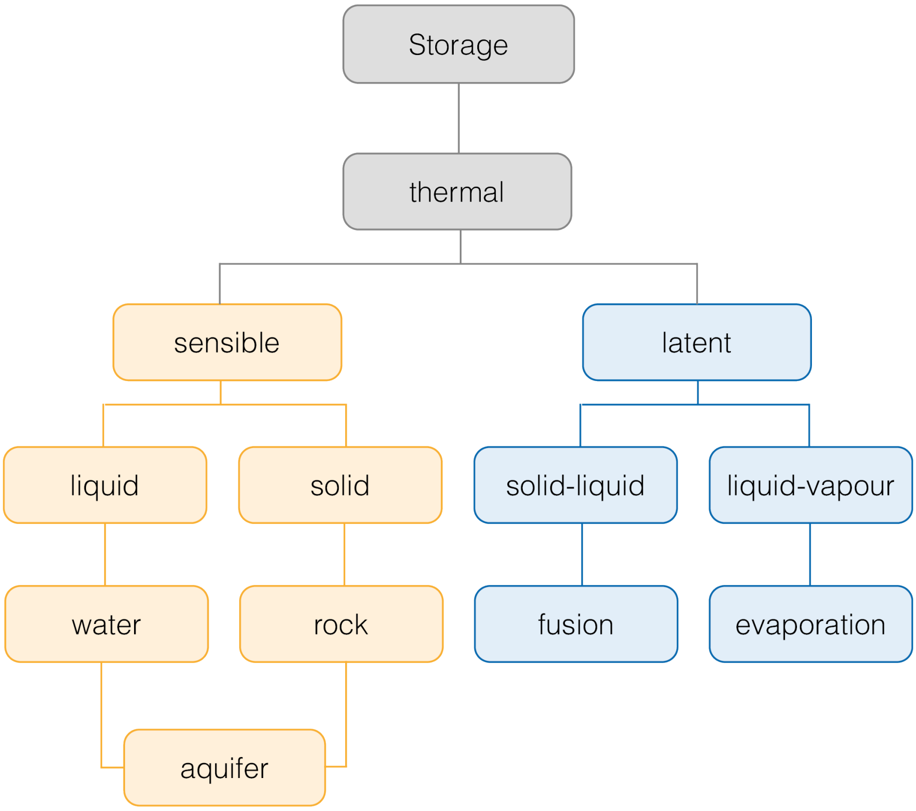
The quantity ρ c_p ($Jm^{-3}K^{-1}$), called *volumetric specific thermal capacity,* is the main parameter for establishing the storage ability of a substance. Although the density of solids such as concrete or rocks is more than twice that of water, the specific heat capacity is almost always between 1/3 and 1/4, so the volumetric thermal capacity of water is *about twice* that of solid materials.

Other parameters have an important role in the choice of a sensible storage. Easy charging/discharging of the storage must be considered. Storage media should be safe, neither toxic nor hazardous to release. Of course, the cost of the medium is another factor to consider. Water, which is considered practically inexpensive, is the most favoured medium. However, the water must be properly contained within a steel or concrete tank, which must be duly insulated to limit thermal losses (or gains). Another element to consider is thermal stratification: a good *thermal stratification* allows for better *storage efficiency*, i.e. the ratio between useful energy taken from the storage and the energy stored. Maintaining stratification is not a simple task for liquids.

In conclusion, water is the most common storage medium, but with pros and cons.

Figure 2

A tree chart representing the various possibilities to obtain a TES)



LIQUID SENSIBLE STORAGE SYSTEMS

Water is by far the most common medium for liquid sensible storage. Thermal oil is sometimes used, particularly when temperatures above 100°C would require pressurized tanks, if working with water.

As mentioned above, *water is the medium with the highest volumetric thermal capacity*. In the range 0-100°C, water density is about 1000 kgm^{-3} (with a variation of less than 2%) and the specific heat capacity is 4.19 kJkg^{-1}K^{-1}, almost constant: the volumetric specific thermal capacity can therefore be evaluated at 4.19 MJm^{-3} K^{-1} (1.16 kWhm^{-3}K^{-1}). The thermal energy that can be stored in a water storage system depends on the temperature difference between the final storage temperature and the lowest useful temperature that can be extracted from the storage. The latter is highly dependent on stratification. Indeed when a hot water storage is discharged, as in the case of a domestic hot water tank, fresh water is supplied to replace the withdrawn water. This lower temperature water tends to mix inside the tank, even if various measures are taken to prevent or at least limit this effect.

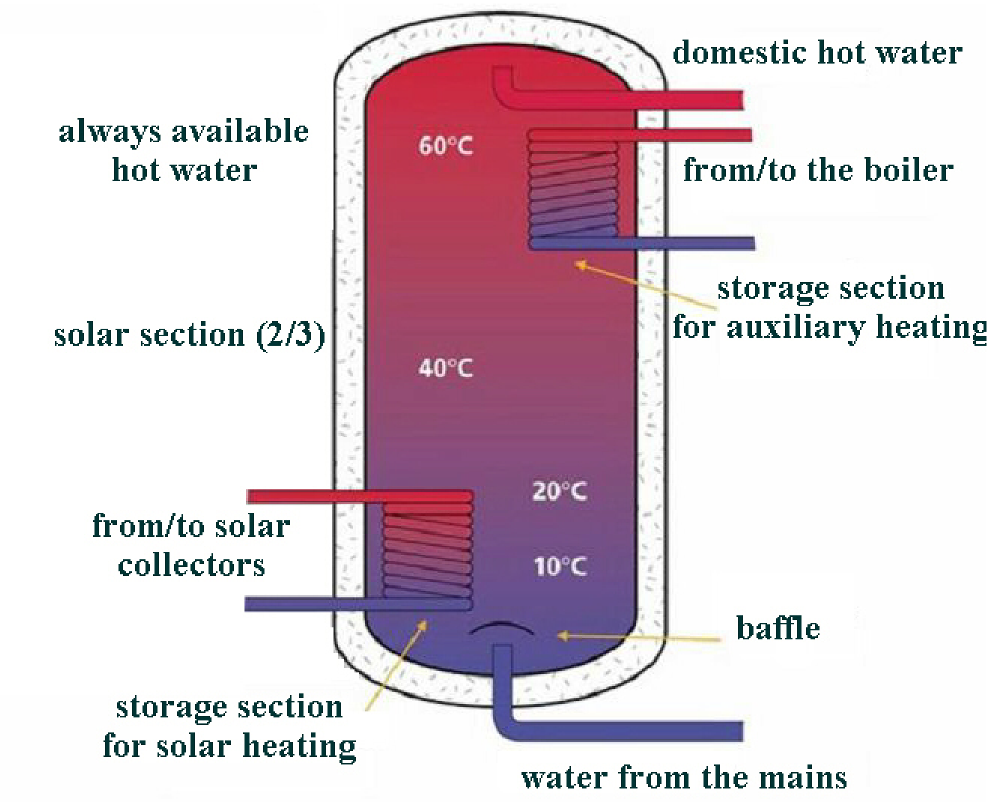
The final storage temperature depends on the energy converter that produces hot water. A heat pump generally operates at lower temperatures (range 50-60°C) than a boiler (range 70-90°C). It also depends on the accepted level of heat losses, taking into account the insulation of the tank. The lowest useful temperature depends on the use: consider the 40°C temperature assumed above for a shower or the minimum level for ambient heating by fan coil, radiator or floor heating. Assuming a temperature difference of 20°C, the volumetric thermal capacity of water can be evaluated at:

$$4.19 \times 20 = 83.8 \text{ MJ m}^{-3} = 23.0 \text{ kWh m}^{-3}$$

Another parameter used is the volume required to store 1 kWh. In this case, the value is 0.04 m^{3}kWh^{-1}. To enhance stratification, a hot water tank should be designed with a prevailing vertical shape if possible. In the domestic hot water tank shown in figure 3, the hot water is withdrawn from the top, where the set temperature is maintained by a conventional boiler, while at the bottom, a possible solar integration is provided. The mains water inlet is at the bottom and a baffle, just above the mains input, tries to prevent mixing, thus preserving stratification.

Figure 3

A domestic hot water storage tank with a possible temperature stratification inside



A steel storage tank does not usually exceed 10 m in height with a height/diameter ratio of about 4. The resulting volume of 50 m^3 allows a storage capacity of 1150 kWh with a temperature difference of 20°C. Larger volume tanks are made of concrete. The *height/equivalent diameter* ratio (equivalent because often the shape is not cylindrical) is then normally less than 0.5. So, a concrete basin with a height of 5 m and an equivalent diameter of 15 m has a volume of about 1,000 m^3 and a storage capacity of over 20,000 kWh. Tanks with a volume of several tens of thousands m^3 have been designed. The storage efficiency of such tanks can reach 80%. High storage efficiency requires a good *thermocline* control. The thermocline is a water layer inside a tank where the water temperature changes drastically from hot to cold (figure 4). This layer can be between 30 and 100 cm thick, generally, the thinner it is, the higher the height/diameter ratio of the tank. This layer can be between 30 and 100 cm thick, generally the higher the height/diameter ratio of the tank, the thinner the layer.

A sensible water storage tank can also operate as a *cold storage*, storing chilled water from the chillers that often operate at night or at hours when electricity tariffs are low. Apart from the lower temperature, the operational features are similar to those of hot storage, but with a smaller temperature difference, rarely more than 10 K, typically with chilled water at 5°C returning to the chillers at 15°C. Here, stratification is really essential and it is difficult to maintain it at such a low temperature difference. Many measures have therefore been implemented to reach safe stratification. For example, one solution is the splitting of a storage basin into multiple tanks (figure 5): a control system allows emptying a chilled water tank, addressing the return to a "warm" tank in the discharging phase. A filled "warm" tank will feed the chiller, addressing the chilled water to a cold tank in the charging phase.

The investment cost of a water storage system can sometimes be shared with the frequent legal requirement of providing a building with a fire prevention basin.

A quite special application of sensible water storage should be mentioned: the *solar pond*. Water added with salt is contained in an outdoor pool. In salt water, the layers increase in concentration with depth. If the bottom layer is completely saturated, it can be heated directly by solar radiation entering the water without any convection inside the pool. In this way, high temperature water can be stored in the bottom layer at over 90°C while the pond surface is at ambient temperature.

Figure 4

Representation of a possible thermocline in a water storage tank

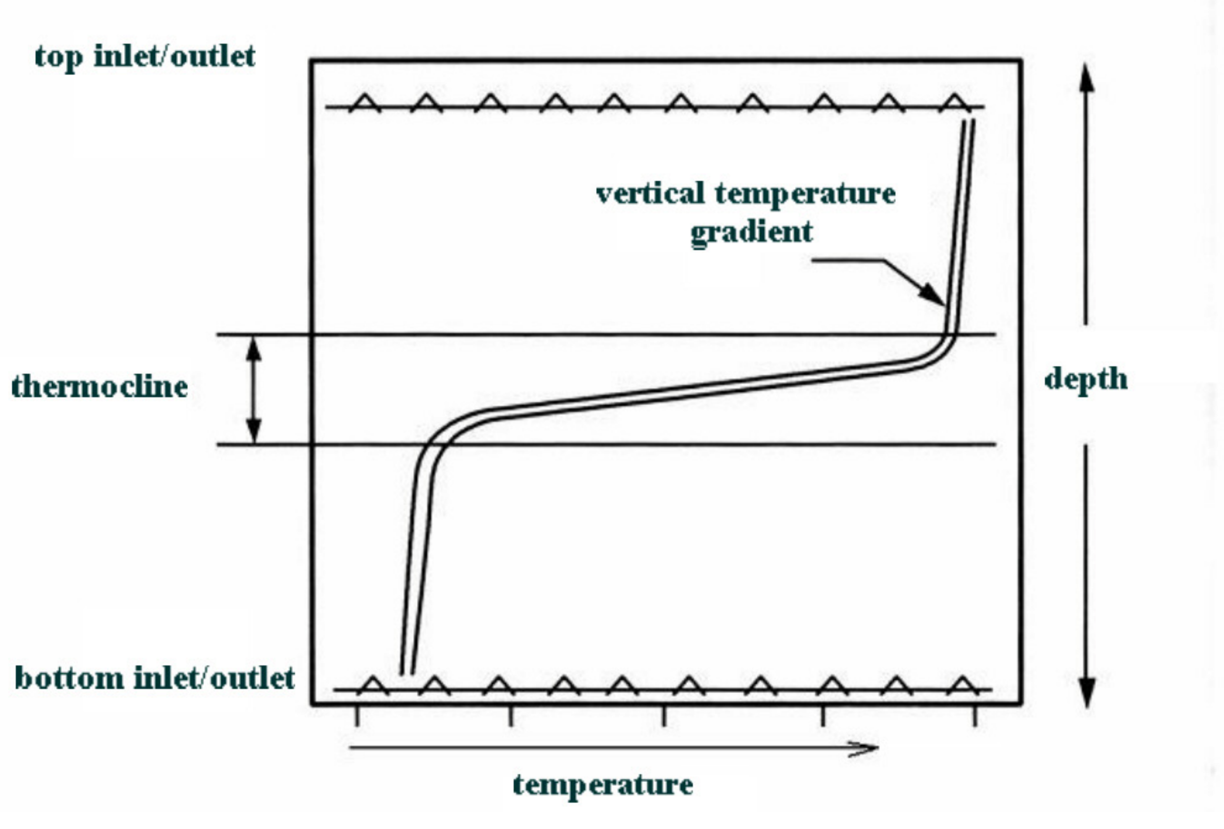
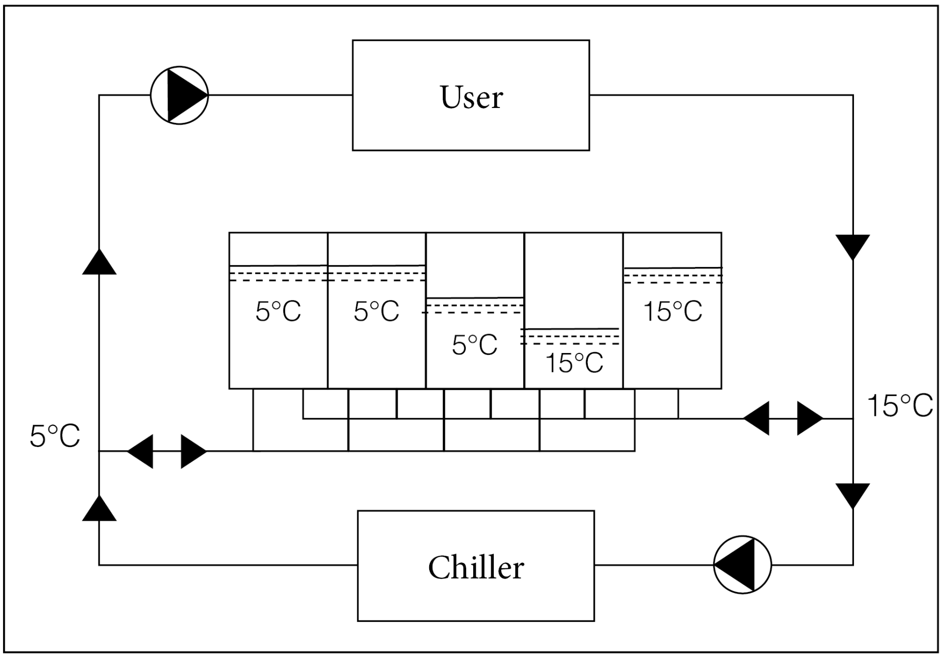


Figure 5
Scheme of a multiple-tank chilled water storage system



SOLID SENSIBLE STORAGE SYSTEMS

Solid media such as rocks, sands, concrete, gravel or bricks can provide a sensible TES that is cheap, non-toxic, non-flammable and less temperature-limited than water. The main drawback is the volumetric thermal capacity which is around half that of water.

The application usually consists in filling a container with pebbles or stones of similar diameter in a packed bed structure. The packed bed is crossed by the heat transfer fluid (generally water or air), so that the storage can be charged or discharged. The heat exchange by direct contact is very effective and the packed bed can allow good thermal stratification. Figure 6 is a representation of a pebble bed. The size of the pebbles can be between 1 and 5 cm. The heat transfer fluid (water or air) flows from the bottom to the top when heat is supplied to the user, while it flows from the top to the bottom when heat is stored. Solar air heating systems are an ideal application of this technology.

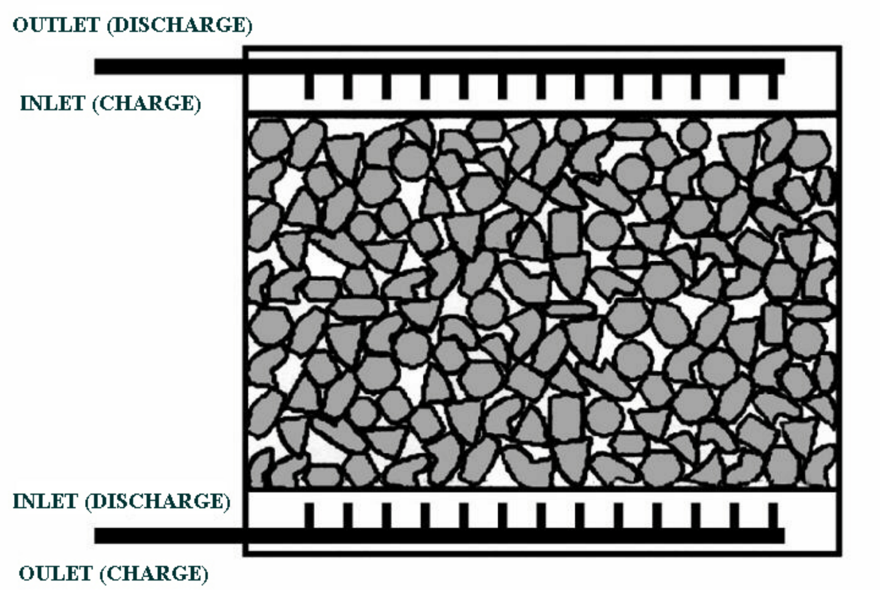
One particular form of thermal storage using a solid medium should be mentioned. This is the so-called *thermal activation of the mass*. A part of a room envelope, often the floor, is made with an additional slab of concrete in order to increase heat capacity with the mass. This reduces peak loads, giving back the heat or cold at a slower pace, thus reducing large fluctuations in outdoor temperature.

A particular application of this concept is the so-called *Trombe wall*, which is a massive Equator-facing wall, covered with a glass on the outside and separated from the wall by an insulating air gap. The absorbed solar energy can be made available to the space behind the wall in a delayed and attenuated manner. In summer, the air gap is arranged to circulate air to prevent the wall from overheating.

Another important application is ground source heat pumps, particularly vertical systems, where a large ground mass is involved, usually with small temperature differences. The ground can act as a heat source, but also as a sink, when the heat pump operates as an air conditioner during the hot season. The ground can then be used alternatively as a heat or cold storage during the year. This function can be of great importance for dual-source solar-ground heat pumps by supplying low level heat to the heat pump during periods of no or low solar radiation in the cold season, while the solar heat recharges the ground during periods of low or no heating demand [4].

Figure 6

A schematic of a pebble-bed solid sensible thermal storage



Latent TES

When a substance changes from one phase to another, for example from a solid to a liquid, a heat transfer called latent heat takes place. This energy absorbed or released during the process has two important characteristics:

- It is *much higher* than the sensible heat for the same substance, even for a wide temperature difference;
- It is absorbed or released *at a fixed temperature* at a given pressure for a pure substance.

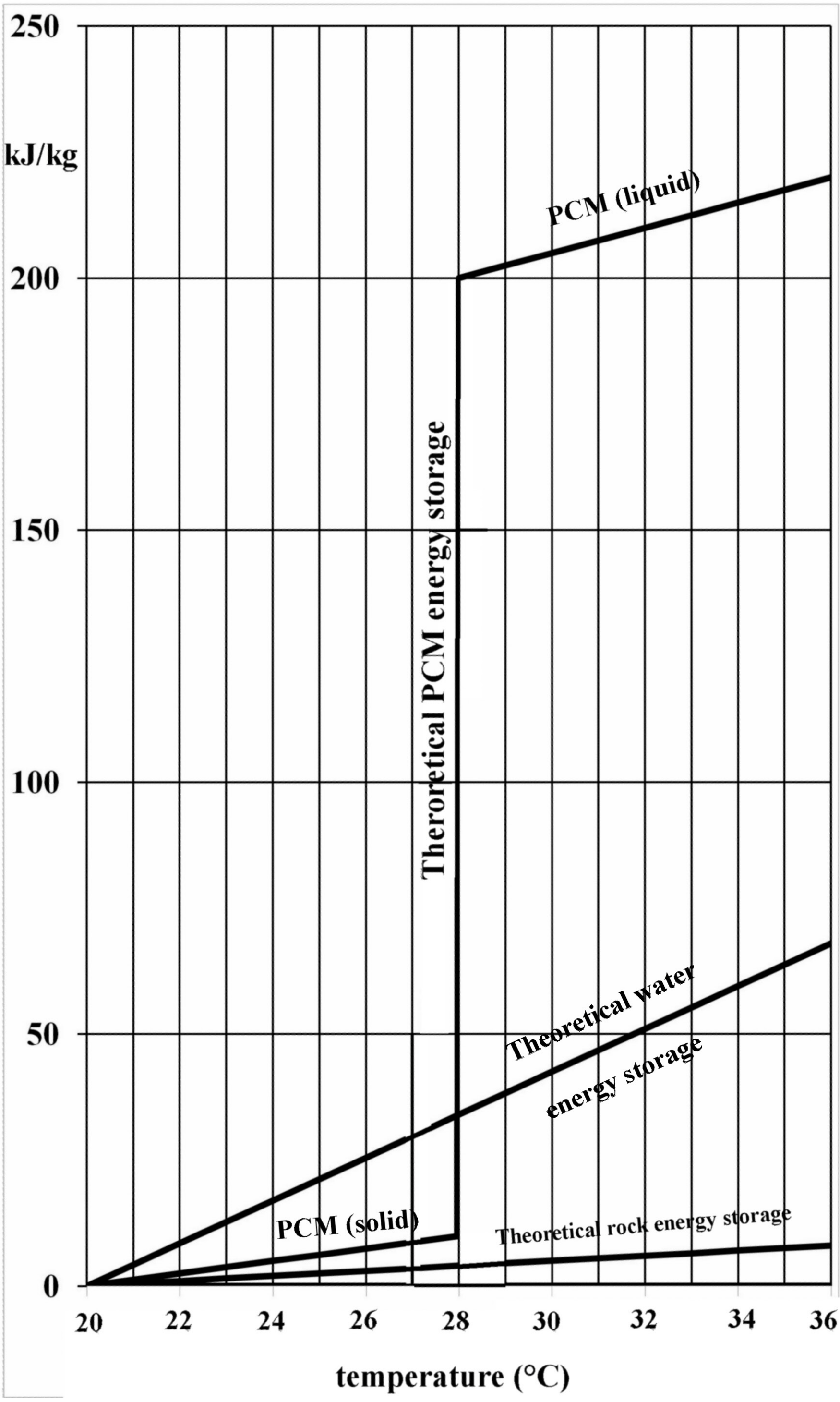
Figure 7 illustrates this behaviour for a *Phase Change Material* (PCM) that changes from a solid to a liquid phase at 27°C at the assigned pressure. First, the solid PCM is heated from 20°C to 27°C with a sensible heat absorption related to the specific heat; then the phase change takes place with a relevant heat absorption typical for a given substance once the pressure is set, called latent heat.

Once all the substance has melted, the temperature of the PCM rises again at a pace dictated by the specific heat of the liquid. Of course, when the substance changes back from liquid to solid, the latent heat is released. In the figure, the possible sensible storage capacity of water or rock is compared with values increasing with temperature difference from 20°C: the slope of the two lines is proportional to the specific heat capacity, which is much higher for water than for rock. PCMs can therefore store or release relevant amounts of energy in comparatively small volumes with modest temperature variations. In principle, the phase change between liquid and vapour could also be used, but the practical application is prevented by the large volume variation. Possible phase changes from one crystalline solid state to another solid state must be mentioned.

A widespread application of PCMs is *cold thermal storage,* which uses the change of phase between liquid water and ice. Water is not only, as mentioned above, practically inexpensive, readily available and harmless, but also compatible with many applications for direct utilisation. Moreover, the latent heat of phase change is very high (334 kJ kg^{-1}), so the specific storage volume is low. As we will see later, many other substances are available today that allow the desired phase change temperature to be selected and provide not only cold thermal storage but also heat storage at various possible temperatures. The latent heat is lower than for water, by 1/3 to 1/2, and although these PCMs are often harmless and readily available, they are expensive, so their cost is an important part of the overall system cost

Figure 7

Storage capacity of a PCM, water or rock, when heating from 20°C to 36°C



ICE STORAGE

Ice storage is dealt with separately from other PCMs because it is by far more widely used and various different technologies are available for forming and melting the ice in the storage system [5]. Ice can be made by a plate or tubular ice maker: a refrigerant circuit is contained inside the plates or tubes, where a refrigerant evaporates to a temperature as low as -15/-20°C. Water flows by gravity outside the plates or tubes, rapidly freezing when its temperature is below 1-2°C. When the ice thickness exceeds 1-2 cm, the circulation of hot gases inside the plates or tubes melts the ice on contact, so that the ice formed is released by gravity into a storage bin below which is the cold thermal storage containing chilled water and ice. Chilled water is pumped from the bottom of the pool directly to the system load, while excess water returns to the ice maker.

Another technology operates with immersed serpentine heat exchanger in a pool of chilled water. A refrigerant evaporates or a chilled brine is circulated inside the serpentine. A layer of ice is formed outside the serpentine, and a control system ensures that the thickness does not exceed 40-60 mm, as too thick a layer would prevent heat transfer between the chilled water and the ice.

A completely different technology forms the ice inside HDP (*HighDensity Polyethylene*) containers of prismatic shape filled with ionised water to which a nucleating agent is added to promote crystallization, reducing the level of water sub cooling, i.e. the temperature difference between the melting point and the beginning of solidification. Each container has a capacity of 4 to 17 L and is flexible to allow for volume expansion during ice formation. These encapsulated ice units are placed in tanks which can be made of concrete, fibreglass or steel in pressurised applications.

A chilled brine circulates through the tank at a temperature below -4°C, so that ice forms in the containers. The brine circulates directly from the tank to the system load during discharge (figure 8).

A completely different system consists in producing a mixture of ice crystals and a liquid water/glycol solution in a slurry state, similar in consistency to a sorbet from an ice cream maker. The advantage is that this ice slurry, contained in a storage tank, can be pumped directly to the load, which may be more than 200 m away. The pumps are of the centrifugal type duly modified for pumping slurry.

The possible advantage of ice storage in terms of low volumetric thermal capacity, which can be as low as 0.019-0.023 m^3 kWh^{-1}, and temperature stability, must be balanced by the higher investment and operating cost, which can be around 20% higher than that of water-based thermal storage. Ice storage allows a cold air distribution system to be used at temperatures about 10°C lower than conventional systems, making the distribution system less bulky and cheaper. However, the air distribution system must be carefully designed to avoid cold draughts. Finally, it should be taken into account that the COP of the chiller will be about 20% lower than that of conventional systems, as the refrigerant evaporates at lower temperatures. Also, PCMs other than ice are sometimes employed for cold TES systems.

Figure 8

Scheme of an encapsulated ice storage system

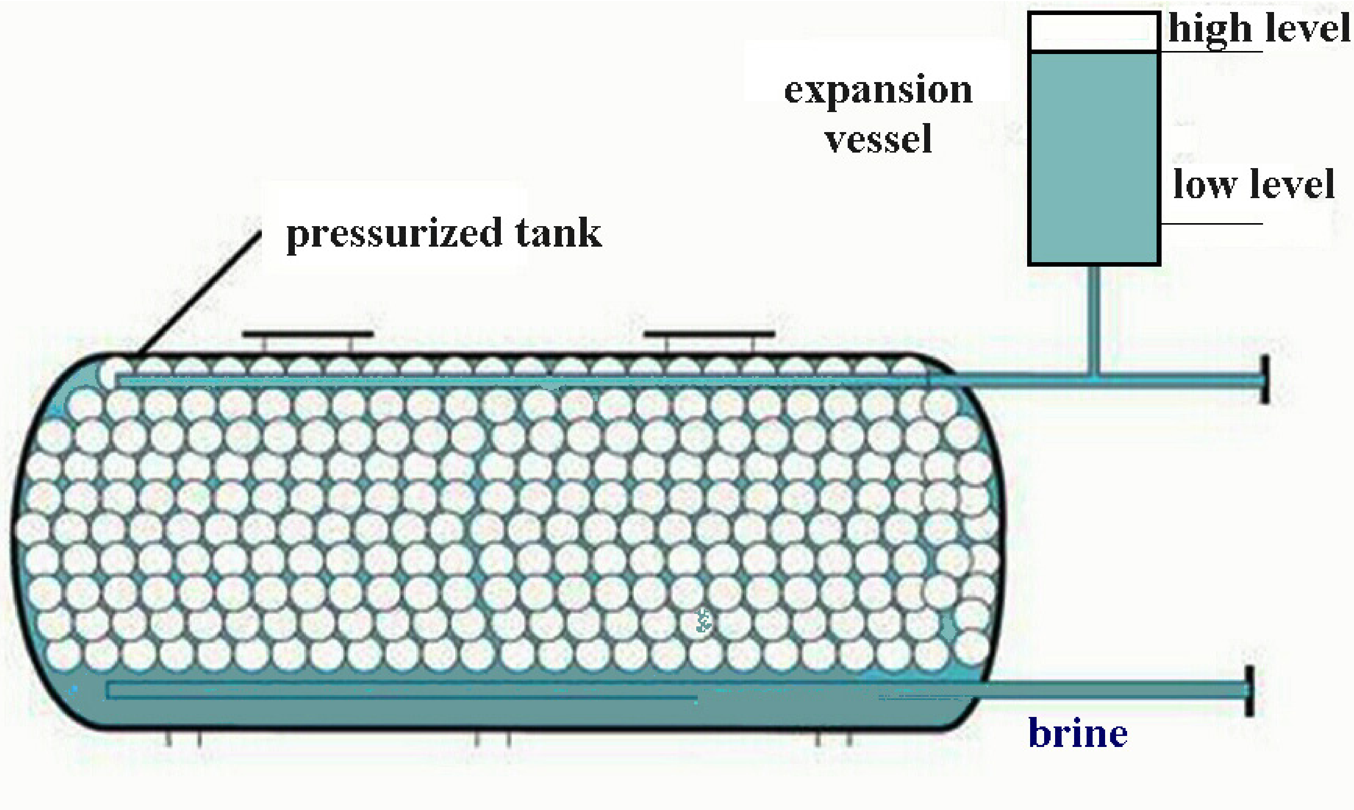
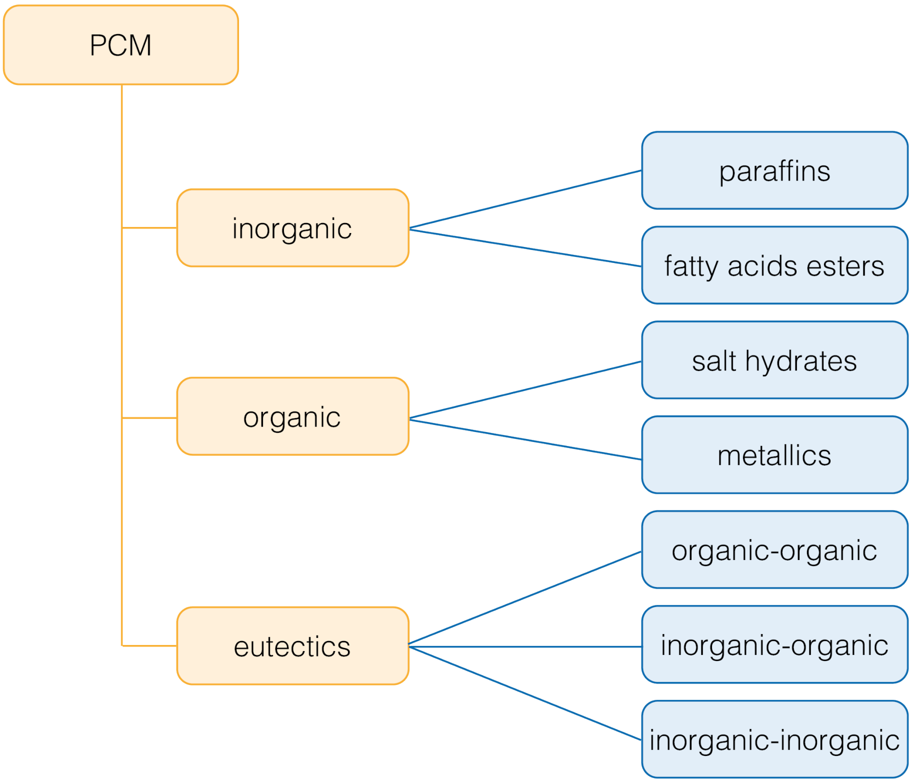


Figure 9
Classification of PCMs



PCM TES SYSTEMS

Apart from water/ice, PCMs include different substances that can be classified as illustrated in the tree diagram in figure 9 [6].

When selecting a PCM, the following characteristics should be considered:

- suitable phase change temperature;
- high latent heat of phase change;
- high thermal conductivity;
- high density;
- low volume change during phase change;
- chemical stability;
- stability after many phase cycles;
- no or very low toxicity;
- low cost and easy availability.

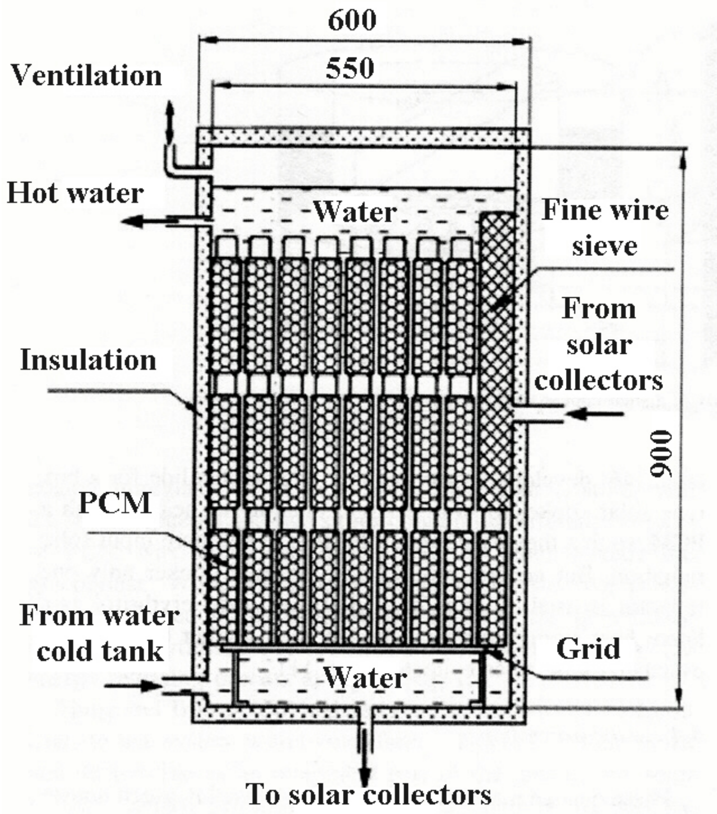
Most of the above criteria are satisfactorily fulfilled by *paraffin* in applications such as space heating, air conditioning or domestic hot water heating. Paraffins are polymers of different composition with a wide range of phase change temperatures (most PCMs change phase from liquid to solid and vice versa). The fusion temperatures of paraffins can range from as low as 4°C to as high as 80°C, with many intermediate temperatures. The heat of fusion is in the range of 100 to 200 $kJkg^{-1}$. The main challenge in using PCMs is probably heat transfer, as the thermal conductivity is only 0.2 $Wm^{-1}K^{-1}$. Consider a container filled with paraffin and, inside, a serpentine heat exchanger in which water is circulated to charge and discharge the storage. In the charging phase, hot water begins to melt the paraffin around the tube with a slowly increasing heat transfer as the liquid paraffin switches from conductive to convective heat transfer. During the discharge, an initial solidification takes place around the tube, introducing an increasing conductive resistance between the water to be heated in the tube and the remaining liquid paraffin. Consequently the available heat flux from the storage tank decreases continuously, remaining in all cases at low values. Similar behaviour is observed in many water/ice storages, but the very low thermal conductivity of paraffin emphasises the problem.

Various measures have been taken to overcome this drawback.

One possibility is to provide a *large heat transfer surface* within the storage tank as represented in Figure 10: the PCM is contained in tubes of small diameter immersed in a tank filled with water. A fine wire or fins surround the tubes to increase the heat transfer area and to enhance heat transfer.

Figure 10

Tubes filled with PCM immersed in a water tank for easy charging/discharging of the storage



A more effective measure is the insertion of high-conductivity materials such as *aluminium foams* into PCM-filled tubes, which can significantly reduce the store loading or unloading time. The reduction can be up to 6-8 times (from 60 minutes to 10 minutes) [7]. The main drawback is the current high cost of metal foams.

A final possible application is the impregnation of PCMs into building materials, either by direct incorporation or, more recently, by microencapsulation. The PCM particles are encapsulated by a film of polymeric material in microcapsules with a diameter of about 1-1000 µm. The encapsulation reduces the reactivity of the PCMs with the outside environment. Moreover, the high surface-to-volume ratio of the capsules improves the heat transfer with the surroundings [8]. An example of application is the insertion of PCM microcapsules in the plaster of a wall, allowing to reduce temperature peaks as described above for thermal activation of the mass, but with a lightweight construction.

Long-term TES

Most TES applications meet short-term demand by storing energy for a period of a few hours to a few days. In many countries of the world, winter is cold (and buildings require heating) and summer is warm or hot (and buildings require cooling). A cold TES charged in winter could satisfy summer cooling demand, just as a hot TES charged in summer would in winter. Such a long-term TES is really a challenge, considering the large storage volume required, the investment cost, the proper management and the risk of heat losses or gains. Nevertheless, some seasonal TES have been designed, mainly in Europe, with a remarkable increase in the supply of high fractions of the heating demand by renewables. The applications were mainly for *district heating* and sometimes for *greenhouses*.

Long-term TES is generally achieved through sensible storage in *aquifers* or *underground soil.* An aquifer is an underground layer of water and permeable rocks that, for TES applications, should be confined with little or no groundwater flow.

If such a formation is available and a geological investigation has deemed it suitable, drilling two wells allows cool groundwater to be extracted in summer from one well, providing a cooling effect and returning water to the other well. From this well, groundwater will be extracted in winter. While *passive cooling* is often effective, the heating phase is usually assisted by *heat pumps.*

When an aquifer is not available, the possible alternatives are *hot water/gravel* water storage or *ground/soil* storage obtained by inserting vertical or horizontal tubes into the ground, in order to involve a large volume of ground.

As far as the first alternative is concerned, some large-scale projects have been carried out in Germany. Two examples can be mentioned:

1 A large hot water TES was built in *Friedrichshafen*, near Lake Constance in 1996 as part of a district heating system serving a residential zone with 33,000 m^2 of heated area. The storage volume was 12,000 m^3 and it received water heated by 4,050 m^2 flat plate collectors. The average solar fraction recorded over a 10-year period (1997-2007) varied between 21 and 33%, well below the design value of 43%. A careful analysis of the performance revealed high thermal losses, in some years even double the design value, possibly due to a return temperature from the district heating network of about 10-15 K higher than expected. Moreover, the lower third of the store was not thermally insulated [9].

2 A gravel/water TES with a volume of 4,500 m^3 was installed in *Eggenstein-Leopoldshafen* (Baden-Württemberg) in 2008 in a district heating network that supplied heat to buildings with a total gross area of 12,000 m^2. Hot water was produced by 1,600 m^2 of flat plate collectors. To limit thermal losses, accurate insulation was provided: the storage was heat insulated at the bottom with 50 cm of expanded glass granules, the thickness of the insulation was between 50 and 70 cm on the side walls with 100 cm of foam glass gravel at the storage lid [10]. Another important measure consisted in operating the TES discharge down to 10°C by using a heat pump which lowered the return temperature of the heating network from 30°C to 10°C, thus increasing the thermal capacity of the TES and reducing heat losses.

The other alternative, *ground/soil* storage, it is the aforementioned well known *borehole* thermal storage, which is widely used for ground source heat pumps. The example reported here is of a *solar district heating* system in Canada [11], which supplies around 90% of the space heating by solar energy in a very cold climate (5200 degrees C-days). The seasonal storage uses approximately 34,000 m^3 of earth and a grid of 144 boreholes, each 35 m deep, equipped with single U-tube heat exchangers.

The residential area served consists of 52 houses. 2,293 m^2 of solar collectors are mounted on roof structures. Without going into details, it can only be noted that in the first year, the TES returned only 152 GJ (6%) of the input energy for heating with 1520 GJ of solar energy supplied directly to the district grid, giving a solar fraction of 55%. In subsequent years, the TES returned increasing fractions of the input energy for progressive charging of such a huge storage, reaching 54% in the fourth year, allowing the contribution of solar energy (from the TES + direct) to the load to increase to 60% in year two, 80% in year three and 86% in year four.

The above described and other seasonal TES experiments have led to technical improvements, cost reductions and higher efficiencies. The reported examples have been discussed in more detail to highlight the technical challenge, but also the high solar fractions that only a seasonal TES can provide.

Another completely different approach is being carefully studied by some researchers: the sorption cold storage. The operating principle resembles that of an intermittent absorption or adsorption refrigerator. In a charging phase, driving heat is applied to a generator and a refrigerant is thus separated from the absorbent. The refrigerant is then condensed and stored in a container for the discharging phase, which can take place even months later. The rich solution obtained in the same way is stored in another container for the absorption system, while a solid desorbent is regenerated for the adsorption system. In the discharging phase, evaporation of refrigerant produces the cooling effect even for subzero applications (this depends on the kind of refrigerant, e.g. ammonia). The refrigerant vapour is absorbed by the rich[2] solution (or by the regenerated adsorbent), releasing the absorption heat, which can be used for heating purpose. The development of these technologies is hindered not only by the huge quantities of absorbent/adsorbent required, but also by many other issues such as the toxicity of ammonia (which is the most recommended refrigerant for subzero applications) or the low thermal conductivities and low porosity characteristics of the adsorbents [8].

[2] *Rich or poor here means low or high concentration of the refrigerant in the absorbent*

Conclusions

Available TES opportunities and technologies were highlighted. Proper application of TES can reduce energy cost and consumption, increasing operating *flexibility* and equipment *efficiency*. The possible reduction in equipment size with lower investment costs should be considered. Moreover, a TES is fundamental to achieve *high free energy fractions with renewables,* particularly in solar power plants. Opportunities offered by a TES in cogeneration, in waste heat exploitation and in any intermittent energy source should be evaluated.

Technologies based on sensible water storage systems are frequently used, as well as ice storage systems, whenever the difference between peak and off-peak tariffs is wide enough. Solid sensible and PCM TES are still niche applications with potential advantages but also limitations to be carefully analysed.

Seasonal TESs are a charming promise for a high solar contribution to heating and cooling of buildings, but further research and experimentation is needed.

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IIR recommendations

Thermal Energy Storage (TES) systems can yield significant benefits in terms of energy savings and cost reduction, with fundamental contributions in the field of renewables. The IIR therefore emphasises the need to:

- Develop strong worldwide campaigns on TES characteristics, performance and cost to raise awareness among potential users, engineers and architects.
- Organise specific courses for designers and installers on the proper choice and installation of TES, selecting the most appropriate technology for a given application depending on the energy source or the process that requires the assistance of a suitable thermal storage capacity.
- Set up incentive schemes and guidelines to promote the most efficient use of TES, especially for building heating and cooling, solar power plants, and district heating/cooling.

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