Thermal energy storage for renewable heating and cooling systems

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7.1 Introduction

7.1.1 Thermal energy storage

7.1.1.1 Principles and requirements

Thermal energy storage (TES) allows the storage of heat and cold for later use. TES is also known as heat or cold storage (Mehling and Cabeza, 2008; Cabeza, 2012). TES can aid in the efficient use and provision of thermal energy whenever there is a mismatch between energy generation and use. This mismatch can be in terms of time, temperature, power, or site (Dincer and Rosen, 2002). The potential advantages on the overall system performance are as follows (Mehling and Cabeza, 2008):

- Better economics—reducing investment and running costs
- Better efficiency—achieving a more efficient use of energy
- Less pollution of the environment and fewer CO_2 emissions
- Better system performance and reliability

The basic principle is the same in all TES applications. Energy is supplied to a storage system for removal and use at a later time (Dincer and Rosen, 2002). A complete process involves three steps (Figure 7.1): charging, storing, and discharging. In practical systems, some of the steps may occur simultaneously, and each step can happen more than once in each storage cycle (Gil et al., 2010).

Several factors have to be taken into consideration when deciding on the type and the design of any thermal storage system, and a key issue is its thermal capacity. However, selection of an appropriate system depends on many factors, such as cost–benefit considerations, technical criteria, and environmental criteria (Gil et al., 2010; Cabeza, 2012).

Recently, storage concepts have been classified as active or passive systems (Gil et al., 2010). An active storage system is mainly characterized by forced-convection heat transfer into the storage material. The storage medium itself circulates through

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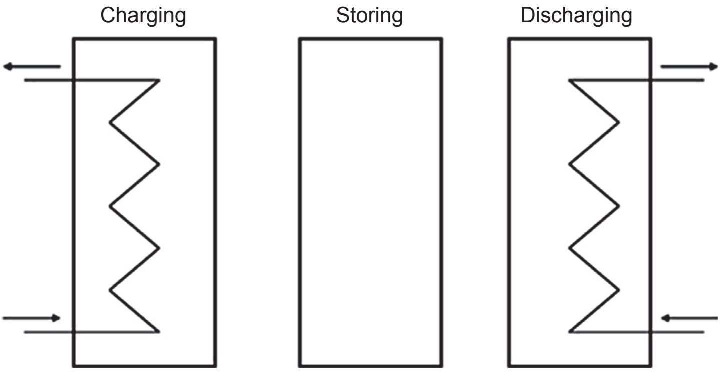


Figure 7.1 Steps involved in a complete TES system: charging, storing, and discharging (Gil et al., 2010).

a heat exchanger (the heat exchanger can also be a solar receiver or a steam generator). This system uses one or two tanks as storage media. Active systems are subdivided into direct and indirect systems. In a direct system, the heat transfer fluid (HTF) serves also as the storage medium, whereas in an indirect system, a second medium is used for storing the heat. Passive storage systems are generally dual-medium storage systems: the HTF passes through the storage only for charging and discharging a solid material.

The cost of a TES system mainly depends on the following items: the storage material itself, the heat exchanger for charging and discharging the system, and the cost of the space and/or enclosure for the TES.

From a technical point of view, the most important requirements are as follows:

- High energy density in the storage material (storage capacity)
- Good heat transfer between HTF and storage medium (efficiency)
- Mechanical and chemical stability of storage material (must support several charging—discharging cycles)
- Compatibility between HTF, heat exchanger, and/or storage medium (safety)
- Complete reversibility of a number of charging—discharging cycles (lifetime)
- Low thermal losses
- Easy control

And the most important design criteria from the point of view of technology are:

- Operation strategy
- Maximum load
- Nominal temperature and specific enthalpy drop in load
- Integration into the whole application system

7.1.1.2 Design of storages

Figure 7.2 shows the basic working scheme of heat storage: heat or cold supplied by a heat source is transferred to the heat storage, stored in the storage, and later transferred to a heat sink to cope with the demand (Mehling and Cabeza, 2008).

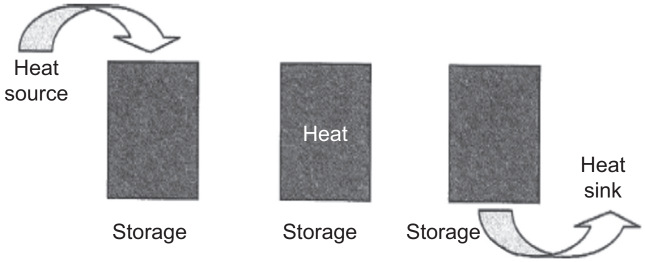


Figure 7.2 Basic working scheme of storage: heat or cold from a source is transferred to the storage, stored in the storage, and later transferred to a sink (Mehling and Cabeza, 2008).

Every application sets a number of boundary conditions, which must be carefully examined:

- From the temperature point of view, the supply temperature at the source has to be higher or equal to the temperature of the storage and the storage to the sink.
- From the power point of view—that is, the amount of heat transferred in a certain time must be that required in the charging and discharging.
- In some applications, the HTF and its movement by free or forced convection have to be considered.

There are three basic design options in storage systems (Mehling and Cabeza, 2008). The first one is when heat is exchanged by heat transfer on the surface of the storage. This becomes a typical heat transfer problem in which heat transfer resistance on the surface of the storage tank is the main parameter. Conduction and free or forced convection mechanisms are to be considered here.

Second, when a heat exchanger is used separating the HTF with the storage material, the surface of heat transfer increases significantly. This surface can be increased even further with the use of fins.

Finally, a third scheme is used when the heat storage medium is also the heat transfer medium. An example is when a water tank is discharged due to the demand of the shower, and cold water enters the tank replacing the hot one. In this case, heat transfer is basically by convection.

7.1.1.3 Integration of storage into systems

The main goal to integrate a heat or cold storage tank into a system is to supply heat or cold. However, the different supply and demand situations have a great influence on the integration concept (Mehling and Cabeza, 2008). The first case to consider is when there is no overlap in time between loading from the supply and unloading to the demand. In this case, the storage system can match different times of supply and demand; in many cases, the storage system can match different supply and demand power, and even supply and demand location, with transport of the storage medium. If there is a partial or total overlap in time, it is possible to smooth out fluctuations of the supply and/or the demand. Thus, the typical goals of storage integration are temperature regulation and power matching. The basic goals of the storage are to match supply and demand regarding the amount of heat and cold and the heating or cooling power at the right time. Although the amount of heat or cold is determined by the size of the storage and the heating or cooling power, which depend mainly on the design of the storage, the integration concept has a large influence with respect to time.

7.1.2 Methods for TES

7.1.2.1 Sensible heat storage

In sensible TES, energy is stored by changing the temperature of a storage medium such as water, air, oil, rock beds, bricks, concrete, or sand. The amount of energy introduced to the storage system is proportional to the temperature lift, the mass of the storage medium, and the heat capacity of the storage medium. Each medium or material has its own advantages and disadvantages, but usually its selection is based on the heat capacity and the available space for storage (Dincer and Rosen, 2002). The amount of heat stored in a material, Q, can be expressed as:

$$Q = m \cdot c_{\mathrm{p}} \cdot \Delta T$$

in which m is the mass of storage material (kg), c_{p} is the specific heat of the storage material (J kg^{-1} $^{\circ}\mathrm{C}^{-1}$), ΔT is the temperature change (°C).

Sensible storage is the most common method of heat and cold storage. Some common materials used in TES systems are presented in Table 7.1 (Dincer and Rosen, 2002). The material must be inexpensive and should have good thermal capacity (ρ c_{p}, ρ is the density) to be useful in a storage application.

Besides the density and the specific heat of the storage material, other properties that are also important for sensible heat storage are operational temperatures, thermal conductivity and diffusivity, vapor pressure, compatibility among materials, stability, heat loss coefficient as a function of the surface area-to-volume ratio, and cost (Gil et al., 2010).

A sensible TES system consists of a storage medium, a container (commonly, a tank), and inlet–outlet devices. Tanks must retain the storage material and prevent losses of thermal energy. The existence of a thermal gradient across storage is desirable (Gil et al., 2010). Sensible heat storage can be made from solid or liquid media. Solid media are usually used in packed beds, requiring a fluid to exchange heat. When the fluid is a liquid, the heat capacity of the solid in the packed bed is not negligible, and the system is called a dual-storage system.

In heating and cooling of buildings, sensible TES is mostly used for domestic hot water, in combisystems (Hadorn, 2005), and for seasonal energy storage.

7.1.2.2 Latent heat storage

When a material stores heat while at phase transition, the heat is stored as latent heat. The solid–liquid phase change process by melting and solidification can store large amounts of heat and cold if a suitable material is selected. Upon melting, while heat is transferred to the storage material, the material still keeps its temperature constant

Table 7.1 Thermal capacity at 20 °C of some common materials used in sensible TES (Dincer and Rosen, 2002)

Material	Density ($kg\ m^{-3}$)	Specific heat ($J\ kg^{-1}\ K^{-1}$)	Volumetric thermal capacity ($\times 10^6$, $J\ m^{-3}\ K^{-1}$)
Clay	1458	879	1.28
Brick	1800	837	1.51
Sandstone	2200	712	1.57
Wood	700	2390	1.67
Concrete	2000	880	1.76
Glass	2710	837	2.27
Aluminum	2710	896	2.43
Iron	7900	452	3.57
Steel	7840	465	3.68
Gravelly earth	2050	1840	3.77
Magnetite	5177	752	3.89
Water	988	4182	4.17

at the melting temperature, also called phase-change temperature (Mehling and Cabeza, 2008). This is one of the main differences with sensible heat (Figure 7.3).

Usually the solid–liquid phase change is studied, but some solid–solid phase changes are of interest in some applications. The amount of heat stored can be calculated by:

$$Q = m \cdot \Delta h$$

in which m is the mass of storage material (kg) and Δh is the phase change enthalpy, also called melting enthalpy or heat of fusion ($J\ g^{-1}$).

Figure 7.4 shows the typical range of melting enthalpy and temperature of common material classes used as phase-change materials (PCMs) (Mehling and Cabeza, 2008). The best known and the mostly commonly used PCM is water, which has been used for cold storage since early times. For temperatures below 0 °C, water–salt solutions are the typically used materials. For temperatures between 0 and 130 °C, paraffins, salt hydrates, fatty acids, and sugar alcohols are used. For temperatures above 150 °C, salts and other inorganic materials are utilized. Many substances have been studied as potential PCMs, but only a few of them are commercialized (Zalba et al., 2003; Cabeza, 2005; Mehling and Cabeza, 2008; Cabeza et al., 2011). The selection of the material to be

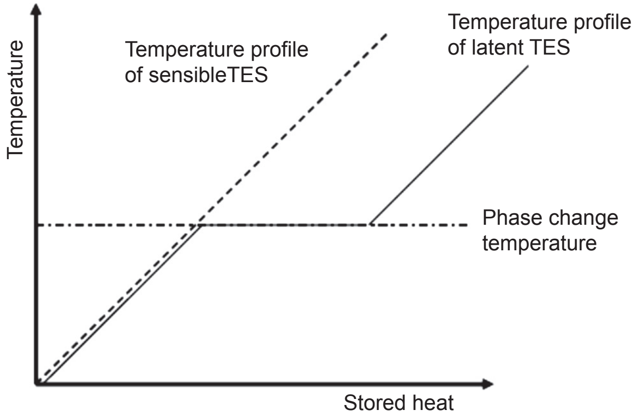


Figure 7.3 Heat storage as sensible and latent TES.

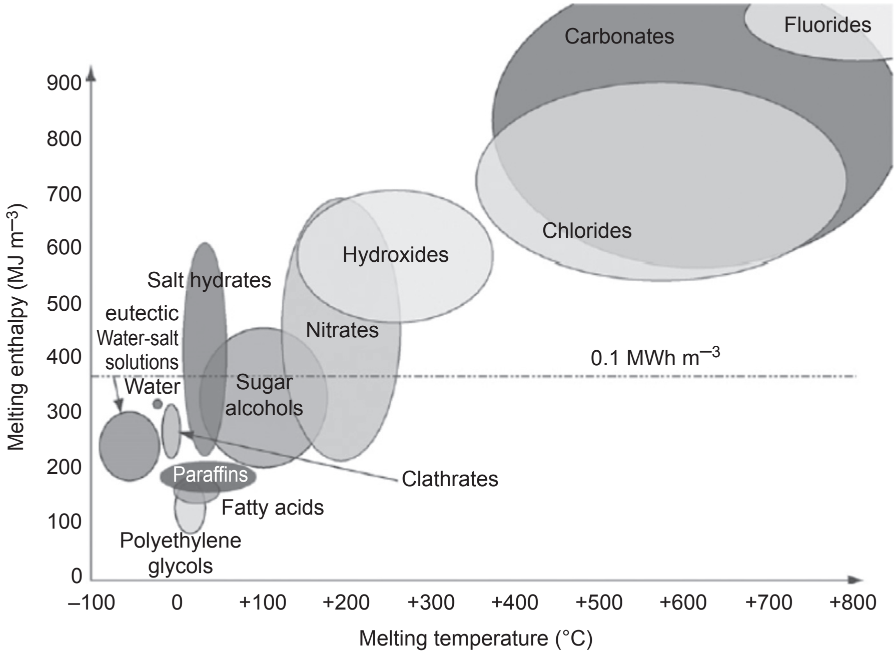


Figure 7.4 Classes of materials that can be used as PCMs and their typical range of melting temperature and melting enthalpy (Mehling and Cabeza, 2008).

used in latent heat storage is not easy. Availability and cost are usually the main drawbacks for the selection of a technically suitable material. Still today, problems such as phase separation, subcooling, corrosion, long-term stability, and low heat conductivity have not been totally solved and are under research.

Table 7.2 **Comparison of organic and inorganic materials for heat storage (Zalba et al., 2003; Mehling and Cabeza, 2008)**

	Organic	Inorganic
Advantages	No corrosives	Greater phase change enthalpy
	Low or no subcooling	
	Chemical stability	
Disadvantages	Lower phase change enthalpy	Subcooling
	Low thermal conductivity	Corrosion
	Flammability	Phase separation
		Phase segregation, lack of thermal stability

PCMs must have a large latent heat and high thermal conductivity, but the most important selection parameter is that the melting temperature of the materials lies in the practical range of operation. Other parameters are congruent melting, minimum subcooling, chemical stability, low cost, nontoxicity, and noncorrosivity. Materials that have been studied are paraffin waxes, fatty acids, and eutectics of organic and nonorganic compounds (Farid et al., 2004; Sharma et al., 2009). Tables 7.2 and 7.3 show two comparisons between organic and inorganic PCMs (Zalba et al., 2003; Mehling and Cabeza, 2008; Rathod and Banerjee, 2013).

According to Kenisarin and Mahkamov (2007), the following PCM properties to be used for latent heat storage were highlighted as desirable:

- High value of the heat of fusion and specific heat per unit volume and weight
- Melting point that matches the application
- Low vapor pressure (<1 bar) at the operational temperature
- Chemical stability and noncorrosiveness
- Not hazardous, highly inflammable, or poisonous
- Reproducible crystallization without degradation
- Small subcooling degree and high rate of crystal growth
- Small volume variation during solidification
- High thermal conductivity
- Availability and abundance

Paraffins are a mixture of pure alkanes that have quite a wide range of the phase-change temperature. These paraffins also have low thermal conductivity compared to inorganic materials, and therefore the choice of those which can be used for practical solar applications is very limited.

Commercial paraffin waxes are cheap with moderate thermal storage densities ($\sim$200 kJ kg^{-1} or 150 MJ m^{-3}) and a wide range of melting temperatures. They

Table 7.3 Comparison of PCM types

	Organic		Inorganic		
	Paraffins	**Fatty acids**	**Salt hydrates**	**Metals**	**Eutectics**
Formula	C_nH_{2n+2} ($n = 12-38$)	$CH_3(CH_2) \cdot COOH$	$AB \cdot nH_2O$	–	–
Melting point	−12–71 °C	7.8–187 °C	11–120 °C	30–96 °C	4–93 °C
Melting enthalpy	190–260 $kJ\ kg^{-1}$	130–250 $kJ\ kg^{-1}$	100–200 $kJ\ kg^{-1}$	25–90 $kJ\ kg^{-1}$	100–230 $kJ\ kg^{-1}$
Cost	Expensive	2 to 3 times more expensive than paraffins	Low cost	Costly	Costly

Adapted from Rathod and Banerjee (2013).

undergo negligible subcooling and are chemically inert and stable with no phase segregation. However, they have low thermal conductivity ($\sim 0.2\ \mathrm{W\,m^{-1}\,K^{-1}}$), which limits their applications.

The main limitation of salt hydrates is their chemical instability when they are heated, as at elevated temperatures they degrade, losing some water content every heating cycle. Furthermore, some salts are chemically aggressive toward structural materials, and they have low heat conductivity. Finally, salt hydrates have a relatively high degree of subcooling.

Salt hydrates are attractive materials for use in TES due to their high volumetric storage density ($\sim 350\ \mathrm{MJ\,m^{-3}}$), relatively high thermal conductivity compared to organic materials ($\sim 0.5\ \mathrm{W\,m^{-1}\,K^{-1}}$), and moderate costs compared to paraffin waxes, with few exceptions.

According to Cabeza et al. (2011), the PCM to be used in the design of a thermal storage system should have desirable thermophysical, kinetic, and chemical properties and desired economics as listed below:

1. Thermophysical properties
   - **a.** Melting temperature in the desired operating temperature range: to assure storage and extraction of heat in an application with a fixed temperature range
   - **b.** High latent heat of fusion per unit volume: to achieve high storage density compared to sensible storage
   - **c.** High specific heat to provide additional significant sensible heat storage
   - **d.** High thermal conductivity of both solid and liquid phases to assist the charging and discharging energy of the storage system
   - **e.** Small volume change on phase transformation and small vapor pressure at operating temperature to reduce the containment problem
   - **f.** Congruent melting of the PCM for a constant storage capacity of the material with each freezing/melting cycle
   - **g.** Reproducible phase change: to use the storage material many times (also called cycling stability)
2. Kinetic properties—nucleation and crystal growth
   - **a.** High nucleation rate to avoid supercooling of the liquid phase and to assure that melting and solidification proceed at the same temperature
   - **b.** High rate of crystal growth, so that the system can meet demand of heat recovery from the storage system
3. Chemical properties
   - **a.** Complete reversible freeze/melt cycle
   - **b.** No degradation after a large number of freeze/melt cycles
   - **c.** No corrosiveness to the construction materials
   - **d.** Nontoxic, nonflammable, and nonexplosive material for safety: for environmental and safety reasons
4. Economics
   - **a.** Abundant
   - **b.** Available
   - **c.** Cost-effective: to be competitive with other options for heat and cold storage

For their use, PCMs must be encapsulated, either encapsulating the material or encapsulating the building composite, as otherwise the liquid phase would be able to flow away from the location where it is applied.

Latent heat storage is used in buildings both in passive and in active systems to reduce the energy demand of the building, to better use renewable energies (solar energy), or for free cooling.

7.1.2.3 Thermochemical heat storage

Any chemical reaction with high heat of reaction can be used for TES if the products of the reaction can be stored and if the heat stored during the reaction can be released when the reverse reaction takes place (Mehling and Cabeza, 2008). A comparison of the energy storage densities achieved with different methods of storage is shown in Table 7.4.

Higher energy storage density and reversibility are required on the materials for thermal energy conversion and storage (Kato, 2007). Energy density of chemical changes is relatively higher than that of physical changes. A merit of chemical energy conversion is the possession of efficient energy storage performance. The performance is especially advantageous for TES. Chemical storage can store energy as reactants with small loss. It is important to find the appropriate reversible chemical reaction for the temperature range of subjected energy source.

TES can be realized by utilizing reversible chemical reactions (Hauer, 2007). Here, the process of adsorption on solid materials or absorption on liquids is explained. Adsorption means binding of a gaseous or liquid phase of a component on the inner surface of a porous material. During the desorption step, heat is put into the sample. The adsorbed component is removed from the inner surface. As soon as the reverse reaction (adsorption) is started, the heat will be released. The adsorption step represents the discharging process. There are two types of sorption systems, closed and open storage systems. In a "closed sorption system," the heat is transferred to and from the adsorbent by a heat exchanger, usually called condenser/evaporator. The heat has to be transported to the absorber at the same time as it is extracted from the condenser to keep the HTF, usually water, flowing from the adsorber to the condenser.

The mechanism of a sorption thermal storage process can be represented by:

$$\mathrm{A}\cdot(m+n)\mathrm{B}+\mathrm{Heat}\leftrightarrow\mathrm{A}\cdot m\mathrm{B}+n\mathrm{B}$$

in which A is the sorbent and B is the sorbate. A/B is called a sorption working pair.

Although sorption thermal storage systems offer some benefits, there are still critical drawbacks, such as great complexity in the system configuration (for closed systems), expensive investment, poor heat and mass transfer ability (for chemical reaction), and low heat storage density in actual systems (Yu et al., 2013).

According to the system configuration, sorption storage systems can be divided into open and closed systems (Hauer, 2007; Yu et al., 2013). Closed sorption systems are not in contact with the atmospheric environment and have been studied for refrigeration, heat pump systems, and energy storage applications (Figure 7.5). Closed systems are adequate for small-scale applications, in which compact and highly efficient devices are needed. Open systems allow the release of the sorbate to the environment

Table 7.4 Comparison of storage densities of different TES methods

Type of storage technology	Material	Energy stored ($MJ\ m^{-3}$)	Energy stored ($kJ\ kg^{-1}$)	Comments
Sensible heat	Granite	50	17	$\Delta T = 20\ °C$
	Water	84	84	$\Delta T = 20\ °C$
Latent heat	Water	306	330	$T_{melting} = 0\ °C$
	Paraffins	180	200	$T_{melting} = 5–130\ °C$
	Salt hydrates	300	200	$T_{melting} = 5–130\ °C$
	Salt	600–1500	300–700	$T_{melting} = 300–800\ °C$
Chemical reactions	H_2 gas (oxidation)	11	120,000	300 K, 1 bar
	H_2 gas (oxidation)	2160	120,000	300 K, 200 bar
	H_2 liquid (oxidation)	8400	120,000	20 K, 1 bar
	Fossil gas	32		300 K, 1 bar
	Gasoline	33,000	43,000	
Electrical storage	Zn/Mn oxide battery		180	
	Pb battery		70–80	

Adapted from Mehling and Gabeza (2008).

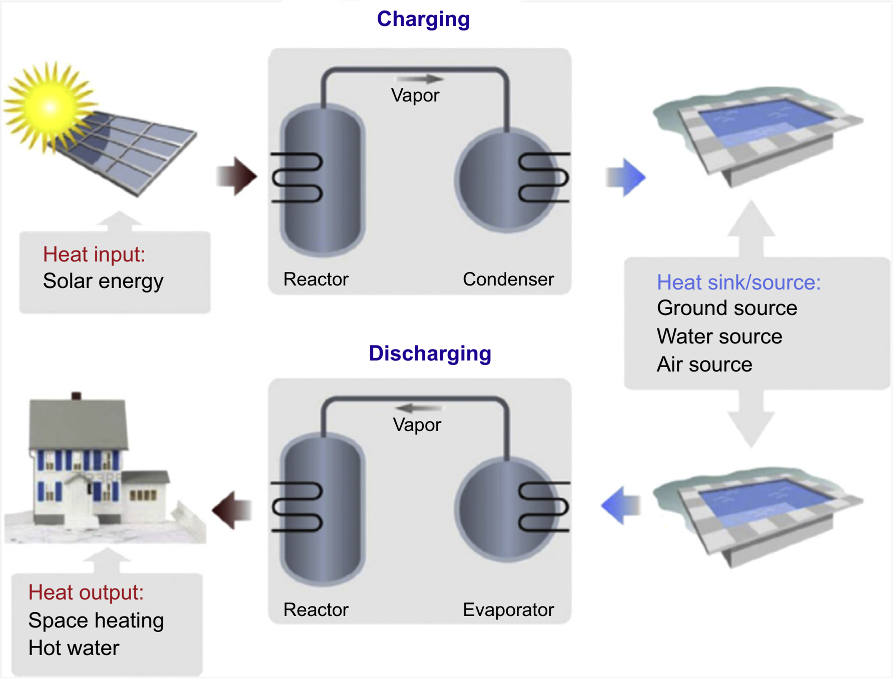


Figure 7.5 Closed sorption thermal energy storage system (Yu et al., 2013).

(Figure 7.6); the sorbate usually is water. These systems have lower investment costs and better heat and mass transfer than closed systems. Thermochemical storage is mostly studied for seasonal TES.

According to Yu et al. (2013), storage materials for thermochemical storage should achieve the following requirements:

- High energy storage density (kWh m^{-3})
- Low charging temperature
- High uptake of sorbate (g sorbate · g $sorbent^{-1}$)

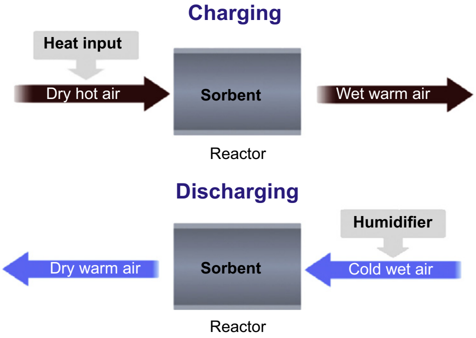
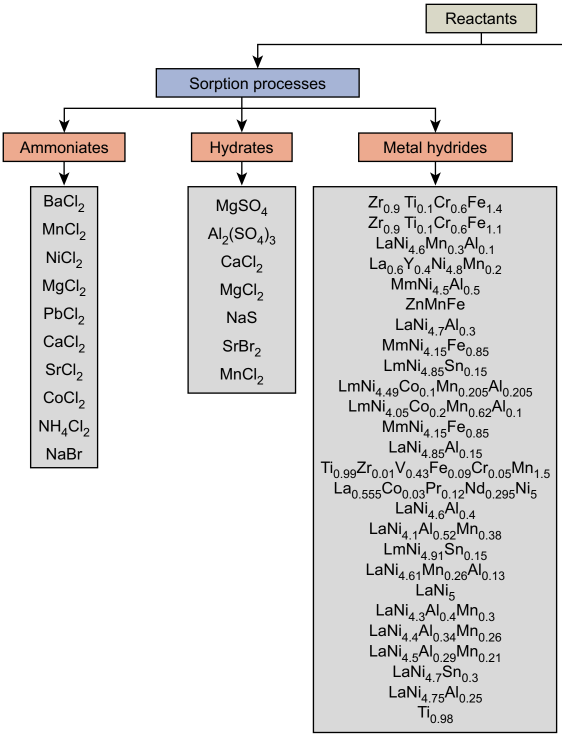


Figure 7.6 Operation principle of an open sorption thermal energy storage system (Yu et al., 2013).



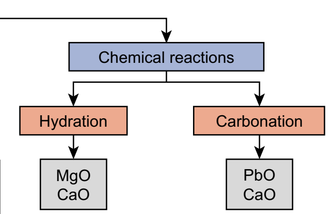


Figure 7.7 Working pairs tested for thermochemical storage (Cot-Gores et al., 2012).

- Appropriate heat and mass transfer properties to ensure designed output power
- Easy to handle, nonpoisonous
- Low cost, low price per kWh heat energy stored
- Thermal stability, no deterioration

The chemical sorption processes found in the literature are those between metal salts with water, ammonia, methanol or methyl-ammonia, and metal alloys with hydrogen (Figure 7.7). Sorption enthalpy typically ranges between 20 and 70 kJ mol^{-1}. A good description of the specific reactants can be found in Cot-Gores et al. (2012).

7.2 Description of TES technologies used today and their applications in the context of renewable heating and cooling

7.2.1 Passive systems in building skins

Passive use of PCMs in buildings has the objective to decrease the operation energy of the building by decreasing the energy demand of space heating and cooling, basically

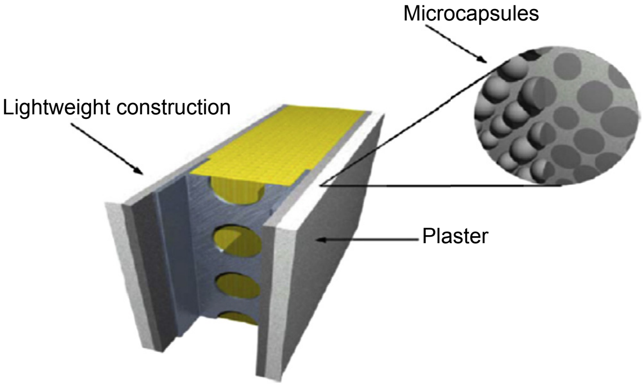


Figure 7.8 Addition of microencapsulated PCMs in a lightweight building (Schossig et al., 2005).

smoothing the indoor temperature by increasing the energy inertia of the building envelope.

One of the oldest options studied and published were PCM wallboards to improve the thermal comfort of lightweight buildings (Sharma et al., 2009), because they are very suitable for the incorporation of PCM (Soares et al., 2013). The efficiency of these elements depends on several factors such as how the PCM is incorporated in the wallboard, the orientation of the wall, the climatic conditions, the direct solar gains, the internal gains, the color of the surface, the ventilation rate, the PCM chosen, and its phase-change temperature, the temperature range over which phase change occurs, and the latent heat capacity per unit area of the wall.

Schossig et al. (2005) showed that PCM can be impregnated into building materials but that when added microencapsulated leakage problems disappear (Figure 7.8). Barreneche et al. (2013) compared in an interlaboratory test the three different methods to incorporate PCM in building materials: microencapsulated, suspension, and impregnation. Although suspension allows the maximum amount of PCM in the building material, only microencapsulation ensures avoiding leakage.

An example of the use of PCM in wallboards was the development of the Dupont product Energain, studied and characterized in several papers (Kuznik et al., 2008a,b; Kuznik and Virgone, 2009; Kuznik et al., 2011). Kuznik et al. (2008a) performed an optimization process using interior/exterior temperature evolutions within a period of 24 h to optimize the thickness of a PCM wallboard to enhance the thermal behavior of a lightweight internal partition wall. The PCM wallboard was composed of 60 wt% of microencapsulated paraffin, which has a melting temperature of about 22 °C (Figure 7.9).

PCM wallboard is considered to be an effective and less costly replacement of standard thermal mass to store solar heat in buildings, in which the PCM is imbedded into a gypsum board, plaster, or other building structures. The thermal characteristics of PCM wallboard are very close to those of PCMs alone, and when a PCM wallboard

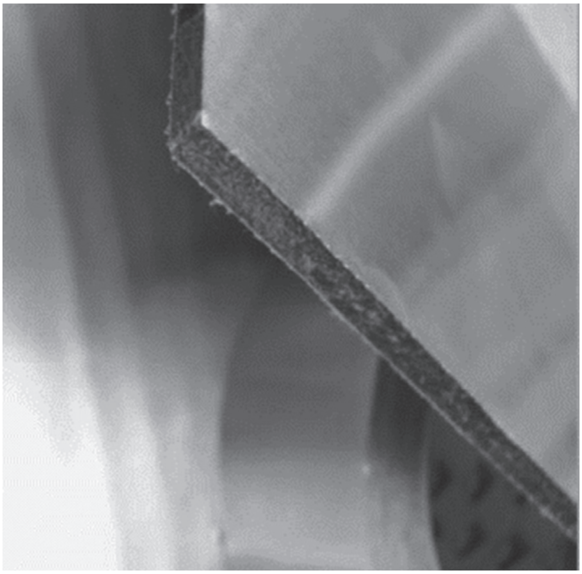


Figure 7.9 Dupont PCM composite wallboard (Kuznik et al., 2008a).

is cut, a greater concentration of PCM lies in the outer third of the wallboard thickness near each face due to the diffusion process (Athienitis et al., 1997).

Athienitis et al. (1997) used a gypsum board impregnated with a PCM in a direct-gain outdoor test room to investigate the thermal performance of PCM gypsum board used in a passive solar building. The results showed that the room temperature can be reduced by a maximum 4 °C during the daytime. Neeper (2000) reported on the impregnation of fatty acid and paraffin waxes into the gypsum wallboard and examination of the thermal dynamics under the diurnal variation of room temperature (the radiation absorbed was not considered) with the PCM on the interior partition and on the exterior partition, respectively. The investigation indicated that when the PCM melting temperature was close to the average room temperature, the maximum diurnal energy storage occurred and diurnal energy storage decreased if the phase change transition occurred over a range of temperature.

To evaluate the capacity of PCM to stabilize the internal environment when there were external temperature changes and solar radiations, Kuznik et al. (2008b) designed an experimental test room MINIBAT using a battery of 12 spotlights to simulate an artificial sunning and they got the results that the PCM wallboard can reduce the air-temperature fluctuations in the room and enhance the natural convection mixing of the air, avoiding uncomfortable thermal stratifications. Kuznik and Virgone (2009) also tested two identical test cells under two kinds of external temperature evolutions, heating and cooling steps with various slopes, and sinusoidal temperature evolution with 24 h period. They found there was time lag between indoor and outdoor temperature evolutions and the external temperature amplitude in the cell was reduced.

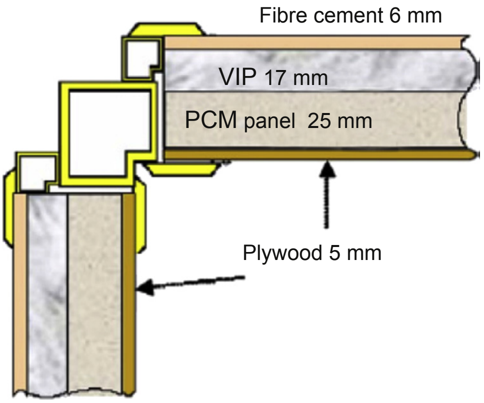


Figure 7.10 Cross-structure of PCM wallboard with vacuum isolation panel (VIP) (Ahmad et al., 2006).

Lv et al. (2006) built an ordinary room as well as a room using PCM gypsum wallboard in the northeast of China, and they found that the PCM wallboards can attenuate indoor air fluctuation, reduce the heat transfer to outdoor air, and have the function to keep warm. Recently, Kuznik et al. (2011) used Dupont de Nemours PCM wallboards for the renovation of a tertiary building and found they were really efficient if the outside temperature was varying in melting temperature by monitoring the building for a whole year. Some researchers reported that using a vacuum isolation panel (VIP) in a wallboard can reduce the thermal loss and improve efficiency for lightweight buildings.

Two test cells were designed by Ahmad et al. (2006), and each cell consisted of one glazed face and five opaque faces insulated with VIPs. One of the cells was equipped with five PCM panels. The cross-structure with PCM wallboard and VIP is shown in Figure 7.10. The amplitude of temperature variation inside the cell with PCM panels was decreased by 20 °C. So in the winter, it helped to efficiently prevent negative indoor temperature. The PCM panels still showed a good thermal storage capability even after more than 480 thermal cycles.

Mandilatas et al. (2013) present one of the first attempts to investigate the thermal performance of a purposely built full-scale lightweight demonstration house constructed in Greece that includes PCM gypsum boards in all external walls as well as in internal partitions of the building (Figures 7.11 and 7.12). Experimental results show that the indoor air temperatures in all thermal zones examined (LVR, MBDR, BDR) do not significantly vary during a 24 h day−night cycle and this can be attributed to the house's enhanced thermal mass associated with the insulation, as well as with the absence of typical occupant behavior.

The use of PCM in building envelopes has been demonstrated in a long-term experimental study at the University of Lleida (Spain). Here, different forms of PCM have been tested in a pilot plant (Figure 7.13) in several identically shaped cubicles with internal dimensions of 2.4 × 2.4 × 2.4 m. The cubicles were built using different typical constructive solutions so concrete cubicles (Cabeza et al., 2007), brick cubicles, and

Figure 7.11 External view of a demonstration house including PCM wallboards (Mandilaras et al., 2013).

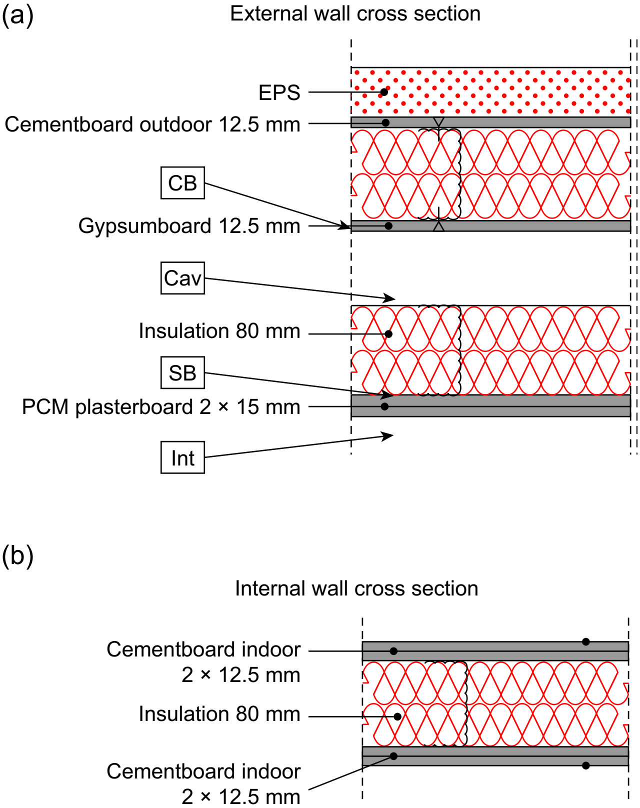


Figure 7.12 Cross section of (a) the external wall ("CB," "Cav," "SB," and "Int" correspond to temperature sensors placed in the LVR east wall); (b) the partition wall with cement boards (Mandilaras et al., 2013).

Figure 7.13 Experimental setup located in Puigverd de Lleida, Spain (Castell et al., 2010).

alveolar brick cubicles (Castell et al., 2010) can be found. In this setup, free-floating temperature and controlled temperature experiments are carried out.

Castellón et al. (2009) show different results of this experimental setup. As an example, results from the brick cubicles are shown here. Figure 7.14 presents the results for free-floating experiments in the brick cubicles, comparing the Reference, PU, and RT27 + PU cubicles during a week in August 2008, when the PCM was working within the phase-change range. As expected, the Reference cubicle always presented higher temperature oscillations and it was also more sensitive to the ambient temperature changes than the PU and RT27 + PU cubicles. When comparing the PU and the RT27 + PU cubicles, the temperature control achieved by the use of PCM was observed. The temperature of the RT27 + PU cubicle remained closer to the phase-change range. The RT27 + PU cubicle remained cooler (about 0.4 °C) during most of the week, when the weather was warmer. At the end of the week (when the weather is cooler) the tendency was reversed, with the PU cubicle being cooler than the RT27 + PU cubicle. This behavior can be explained by the higher thermal mass of the PCM cubicle, which slows down the general cooling tendency that occurs in the last days of the week. The effect of the PCM is also visible in the reduction in the daily oscillations of the inside temperature in the RT27 + PU cubicle. It is also observed that the effect of the PCM is only partially used, as there is no single 24 h period in which full melting and solidification are achieved.

Figure 7.15 and Table 7.5 present the results of the controlled temperature experiments using a set point of 24 °C for a week in August, 2008. The accumulated energy consumption of the Reference cubicle is much higher than all the other cubicles, with about twice the consumption of the other cubicles. The RT27 + PU cubicle is the one with the lowest energy consumption, whereas the SP25 + Alveolar cubicle is the second one, consuming even less energy than the PU cubicle. Finally, the Alveolar cubicle is the one that consumes more energy after the Reference cubicle. Both PCM cubicles reduced the energy consumption compared with the same cubicle without PCM. The RT27 + PU cubicle achieved a reduction of 14.75% compared with the PU cubicle, whereas the SP25 + Alveolar cubicle reached 17.12% of energy savings compared with the Alveolar cubicle (Table 7.5).

Investigations on PCM floors and PCM ceilings for passive solar heating have been carried out during the past few years. Xu et al. (2005) used shape-stabilized PCM floors in passive solar buildings and developed a model to analyze how various factors influence the thermal performance, such as thickness of PCM layer, melting

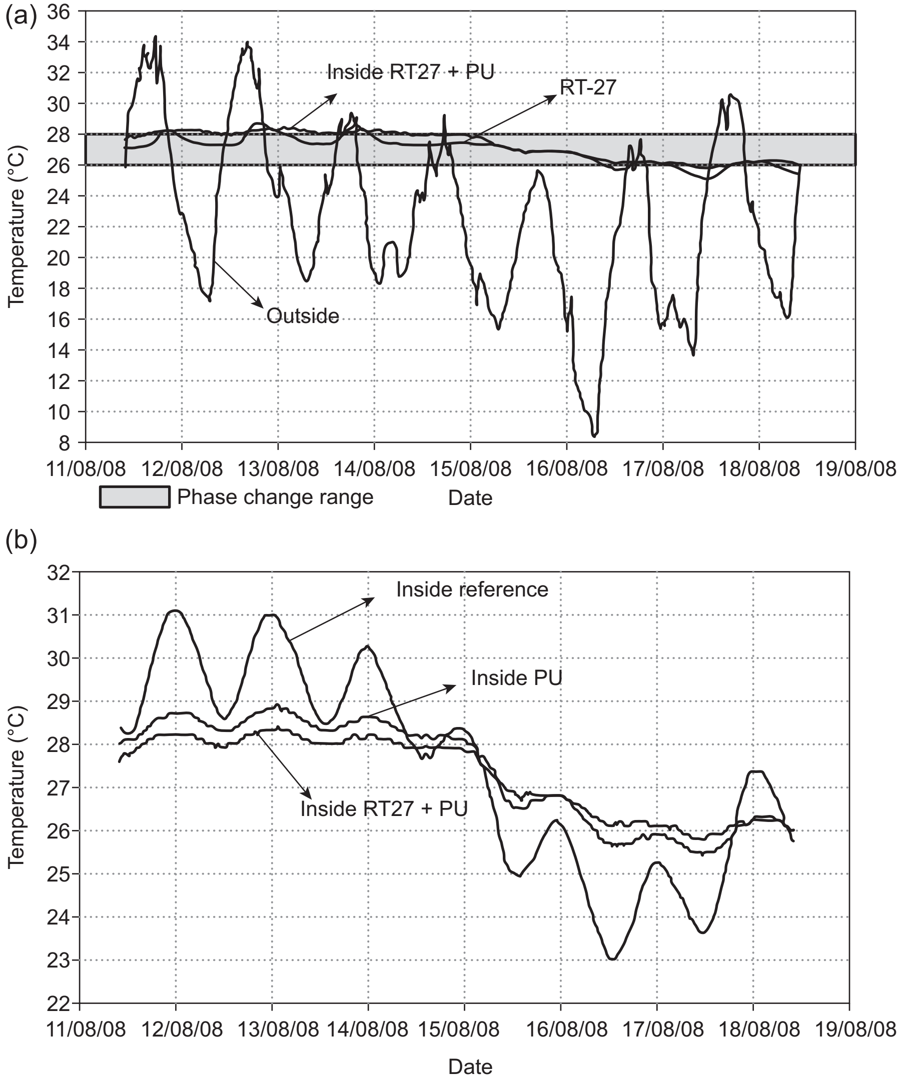


Figure 7.14 Brick cubicles free-floating experimentation: (a) Weather conditions and PCM operating temperature; (b) indoor ambient temperature for Reference, PU, and RT27 + PU cubicles (Castellón et al., 2009).

temperature, heat of fusion, and thermal conductivity of PCM. They indicated that the heat of fusion and thermal conductivity of PCM should be larger than 120 kJ kg^{-1} and 0.5 W m^{-1} K^{-1} and that the thickness of shape-stabilized PCM plate should not be larger than 20 mm. Pasupathy and Velraj (2008) studied the effect of the building with a PCM panel on the roof from the aspect of the location and thickness. They recommended a double-layer PCM to be incorporated in the roof to narrow indoor air temperature variation and to better suit it for all seasons.

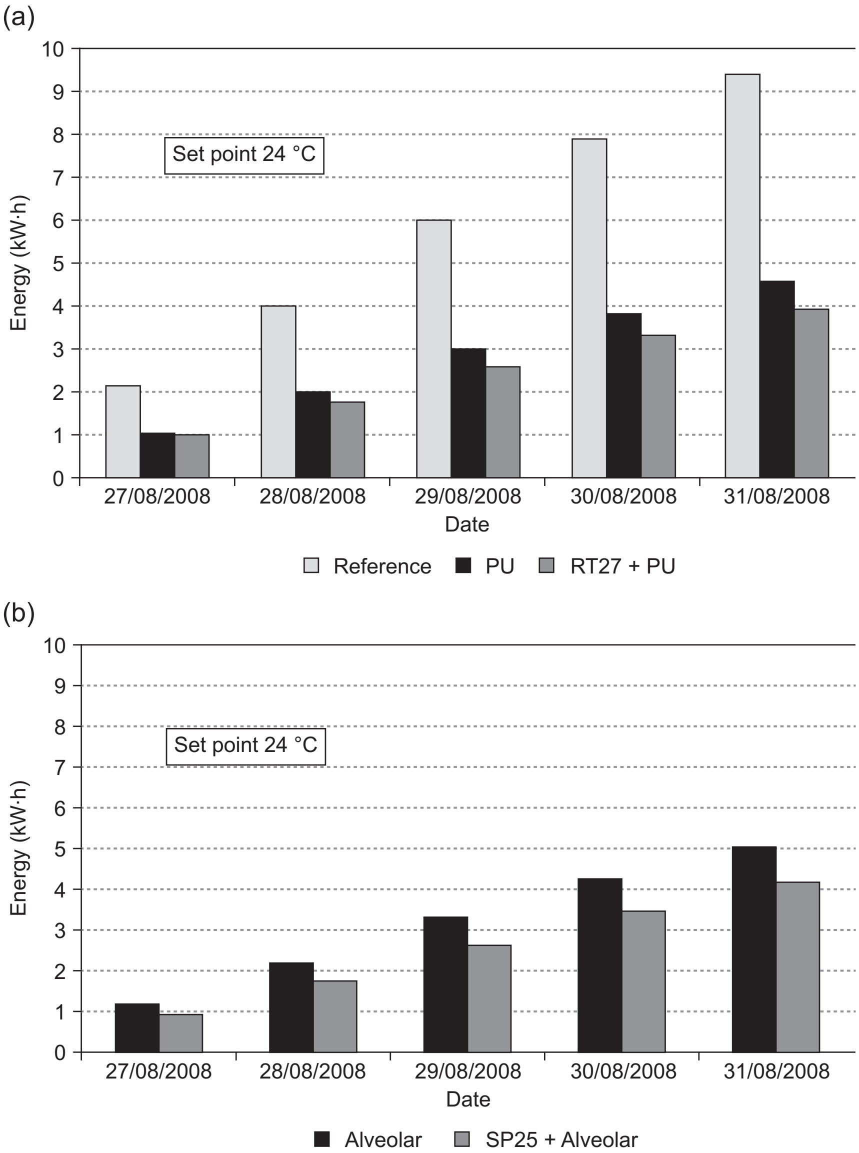


Figure 7.15 Energy consumption of the heat pumps in cooling mode for 5 days in August 2008: (a) Reference, PU, and RT27 + PU; and (b) Alveolar and SP25 + Alveolar cubicles (Castellón et al., 2009).

Many other examples of passive solar systems using PCM can be found in the literature and summarized in the different reviews published (Zalba et al., 2003; Farid et al., 2004; Kenisarim and Mahkamov, 2007; Cabeza et al., 2011; Sharma et al., 2009; Rathod and Banerjee, 2013; Soares et al., 2013).

Table 7.5 **Accumulated energy consumption and energy savings for the different cubicles (Castell et al., 2010)**

	Energy consumption (Wh)[a]	Energy savings (Wh)[b]	Energy savings (%)[b]	Improvement (%)[c]
Reference	9376	0	0	–
PU	4583	4793	51.1	0
RT27 + PU	3907	5469	58.3	14.8
Alveolar	5053	4323	46.1	0
SP25 + Alveolar	4188	5188	55.3	17.1

[a] Set point of 24 °C for 5 days.
[b] Referred to the reference cubicle.
[c] Referred to the cubicle with analog constructive solution and w/o PCM.

7.2.2 Active systems

Active systems using TES in buildings have the aim to decrease the operational energy of the building by decreasing the use of fossil fuels in heating, cooling, and domestic hot water production.

7.2.2.1 Water heating systems

Water storage tanks are made of a wide variety of materials, such as steel, aluminum, reinforced concrete, and steel (Tatsikjoudoung et al., 2013). Moreover, they are usually insulated with glass wool, mineral wool, or polyurethane. Water storage tank energy efficiency and performance are improved when stratification is increased.

In solar water heating systems, the use of PCM can be an advantage because the volume of the necessary water storage tank can be decreased (Cabeza et al., 2006). The PCM module geometry adopted in this study was to use several cylinders at the top of the water tank. A granular PCM—graphite compound of about 90 vol% of sodium acetate trihydrate and 10 vol% graphite was chosen as the PCM for the experiments presented here. The experiments presented in this paper showed that the inclusion of a PCM module in water tanks for domestic hot water supply is a very promising technology. It would allow having hot water for longer periods of time even without exterior energy supply or to use smaller tanks for the same purpose.

This concept of adding PCMs in solar water systems is quite controversial in the bibliography, because although results such as those from Cabeza et al. (2006) show the benefits, Talmatsky and Kribus (2008) carried out a numerical study in which annual simulations were done for different sites, load profiles, different PCM volume fractions, and different kinds of PCMs, showing that, contrary to the expectation, the use of PCMs in the storage tank does not yield a significant benefit in energy provided to the end user. Later, Kousksou et al. (2011) confirmed these findings regarding the use of PCMs but claimed that it seems highly desirable to incorporate a mathematical optimization at the early stages of the design process to achieve more realistic results.

The other big application of water storage systems is the combisystem, in which DHW and heating are produced. Streicher and Bales (2005) stated that one of the key elements of a solar heating system is the hot water store, which has to fulfill several tasks:

- Deliver sufficient energy to the heat sink
- Decouple mass flows of heat sources and heat sinks
- Store heat from unsteady heat sources (solar) from times when excess heat is available to times when too little or no heat is available (either short-term storage from day to night or over one to a few days, or seasonal storage)
- Extend the running times for auxiliary heating devices to increase their efficiency and lower startup/shutdown emissions
- Allow a reduction in heating capacity of auxiliary heating devices
- Store the heat at the appropriate temperature levels without mixing (stratification) to avoid energy losses

The design of the water store in a combisystem greatly affects the overall system performance. The principle of a water store connected to a solar system and with auxiliary heat input is shown in Figure 7.16. In these systems, the stratification of the hot water is of great importance, and charging and discharging must be done carefully considering this fact. This is why water tanks use stratifying units (Figure 7.17).

7.2.2.2 PCM in HVAC systems

The use of night cooling ventilation in addition to PCM is a very powerful strategy for reducing the cooling demand of buildings. Nevertheless, there are inherent drawbacks in the way things have been done so far:

- The limited area of contact between PCM and the air
- The very low convective heat transfer coefficient, which prevents the use of significant amount of PCM
- The very low utilization factor of the cool stored due to the large phase shift between the time when cool is stored and when it is required by the building

A very powerful well-known strategy for reducing the cooling demand of buildings is the use of low outdoor air temperatures during the night to cool the structures of the building. In many cases, the nighttime outdoor air climatic conditions of many Mediterranean locations allow a significant compensation of the daytime solar and internal heat gains (Allard et al., 1998).

The performance of a night cooling application depends on (Alvarez et al., 1997):

- The climate, which provides the availability of the heat sink in terms of its thermal level and its variability throughout the year and on a daily basis.
- The cooling needs of the building (absolute values and load profiles). The combination of 1 and 2 gives the extent to which the requirements can be covered by the cooling technique.

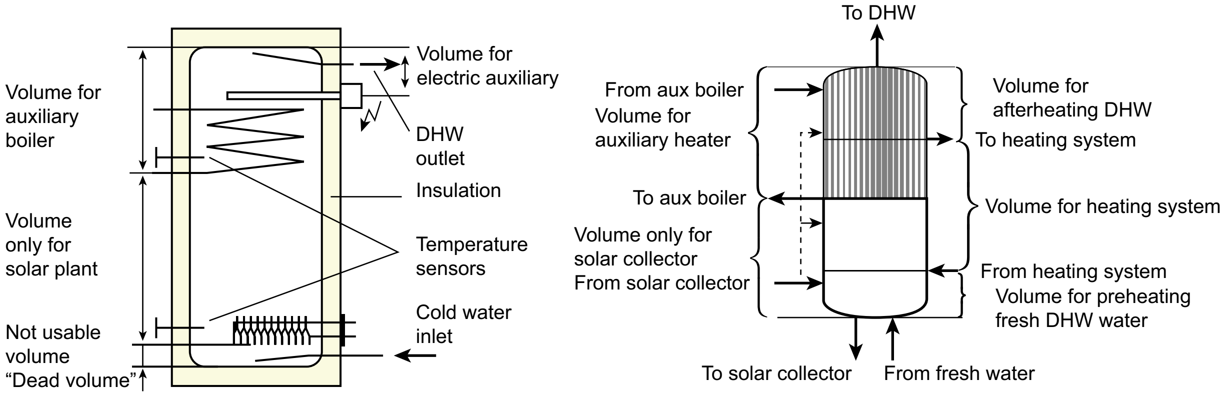


Figure 7.16 Zones for hot water of a DHW system (left) and a solar combisystem (right) (Streicher and Bales, 2005).

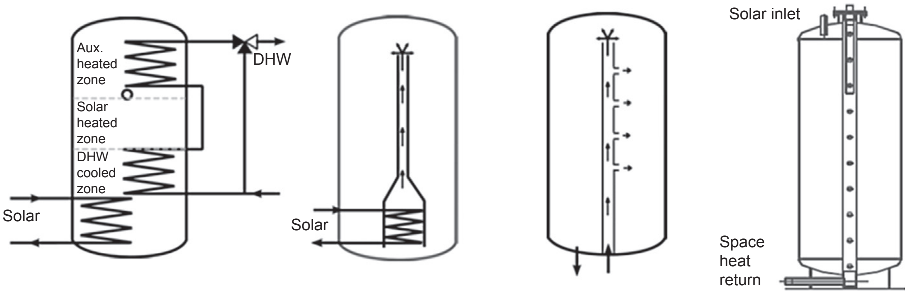


Figure 7.17 Four different stratifying devices for solar water tanks (Streicher and Bales, 2005).

The efficiency of the technology used to transfer heat from the heat sink (nighttime outdoor air) to the building.

The efficiency of a night-cooling strategy lies in the ability of the building inertia to store cool during the night and to use it during the next day. The role of inertia appears then double-linked to this strategy. It can be characterized by means of the storage efficiency and the utilization factor (Allard et al., 1998; Alvarez et al., 1997).

There are several alternatives to incorporate PCM in buildings. Tyagi and Buddhi (2007) present a classification consisting of three types:

- PCMs in building walls
- PCMs in other building components (for example, subfloor or ceiling systems)
- PCMs in separate heat- or cold-storage systems

Athienities and Chen (2000) showed the possibility of using PCMs in underfloor heating systems. The idea is the use of a radiant heating system but with increased performance due to the inclusion of PCMs. The costs have been shown to be reduced if the PCM is used with electrically heated underfloor systems due to the reduction of peak loads and to the use of cheaper night electricity. Similarly, Nagano et al. (2000) presented a floor air-conditioning system with latent heat storage in buildings. Floor size of the experimental cell was 0.5 m^2. Granulated PCM was made of foamed-waste glass beads and a mixture of paraffin. The PCM-packed bed of 3 cm thickness was installed under the floorboard with multiple small holes. The change in room temperature and the amount of stored heat were measured, and results showed the possibilities of cooling load shifting by using packed granulated PCMs.

These new solutions use PCMs in containers, which are located inside an air chamber, in which air is moved by fans with variable flow (forced convection). This air flow is controlled by a control system that can change the air-flow rate, the origin, and the destination of air flow. They even can totally stop the system. The PCM containers are sealed, made of a material that does not react with the PCM contained, and stimulate heat exchange with air around them. In principle, three basic forms have been considered: fins, cylinders, and spheres.

In addition, ceiling boards can incorporate PCM for heating and cooling of buildings. An example is that developed by Kodo and Ibamoto (2002), in which PCMs are used for peak-shaving control of air-conditioning systems in an office building

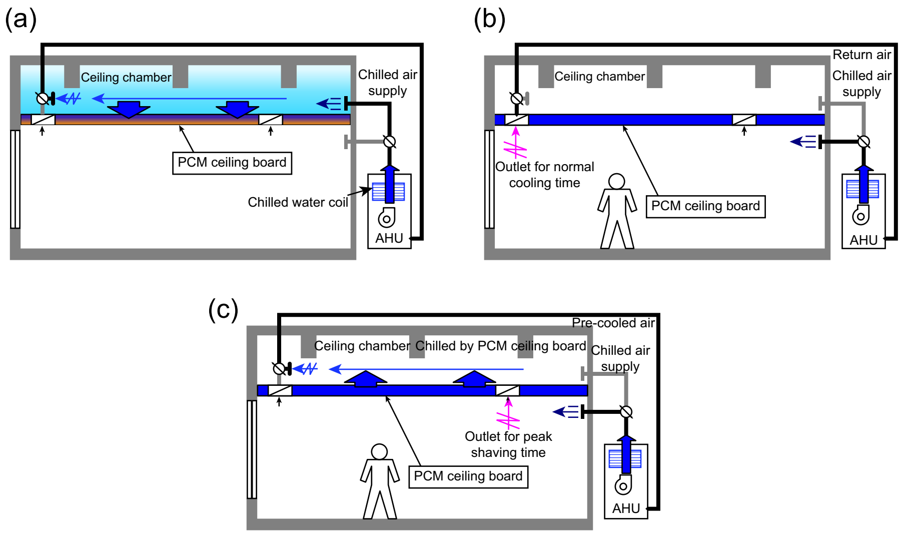


Figure 7.18 Ceiling board with PCM for cooling peak shaving: (a) overnight thermal storage time; (b) normal cooling time; (c) peak-shaving control time (Kodo and Ibamoto, 2002).

(Figure 7.18). The authors claim that these systems have some advantages over conventional building thermal storage systems that use concrete floor slabs:

1. More efficient thermal storage is expected, because high-density cool air pools on the PCM ceiling board that forms the floor of the ceiling space.
2. All of the ceiling board can be used for thermal storage, because the cool air can flow through the ceiling chamber without being interrupted by beams.
3. Because the surface temperature of the ceiling board is kept at the PCM melting point for an extended period, the indoor thermal environment, including the radiant field, can be improved.

Ceiling boards incorporated with PCMs for air-conditioning systems play an effective role on the peak-shaving control. Saman and Belusko (1997) developed a roof-integrated solar air-heating storage system. The latent heat storage unit, in which an existing corrugated iron roof sheet is used as solar collector, is to store heat during the day and supply the heat at night or when sunshine is unavailable. Besides experimental analysis, many numerical works were also carried out on the thermal performance analyses of this system (Vailaltojjar and Saman, 2001; Saman et al., 2005).

Koschenz and Lehmann (2004) put forward a new concept of thermally activated ceiling panel for refurbished buildings. In this system, the mixture of microencapsulated PCM and gypsum was poured into a sheet-steel tray, which was used as a support for maintaining the mechanical stability of the panels. A capillary water tube system was applied to control the thermal mass. They tested the thermal performance of this system and indicated that only a 5 cm layer of microencapsulated PCM and gypsum was enough for a standard office to keep within comfortable temperatures.

Figure 7.19 Experimental setup to test a ventilated façade with macroencapsulated PCMs in its air cavity located in Spain (de Gracia et al., 2013a).

A new type of ventilated façade with macroencapsulated PCM in its air cavity was developed by de Gracia et al. (2013a). The thermal performance of this special building envelope was experimentally tested to analyze its potential in reducing the cooling demand during the summer season (de Gracia et al., 2013a) and the winter season (de Gracia et al., in press) in the Continental Mediterranean climate, and it was numerically extrapolated to different performance scenarios (de Gracia et al., 2013b). Two identical house-like cubicles located in Puigverd de Lleida (Spain) were monitored during summer 2012, and in one of them, a ventilated façade with PCM was located in the south wall (Figure 7.19). Six automatized gates were installed at the different openings of the channel to control the operational mode of the façade. This versatility allows the system to be used as a cold storage unit, as an overheating protection system, or as a night free-cooling application. The experimental results demonstrated the high potential of the night free-cooling effect in reducing the cooling loads of a building. This operation mode could inject air at a temperature below the set point under both severe and mild summer conditions (34.9 MJ day^{-1} and 42.8 MJ day^{-1}, respectively). The system can successfully prevent the overheating effect between the PCM solidification and melting periods, because the air inside the cavity was even lower than the outer environmental temperature during the peak load. The thermal performance of this system is very sensitive to the weather conditions and the cooling demand of the final users.

7.2.2.3 Sorption systems

Only a few applications using liquid absorption can be found. Ruiter (1987) presented an absortion TES cycle using H_2O/NH_3. An experimental setup was built with a net heat output of 5 kW and a storage capacity of 40 kWh. The energy density reached was 111.1 kWh kg^{-1}, based on the total mass of absorbate and weak solution.

Figure 7.20 Double-stage NaOH/H_2O prototype built at the Swiss Federal Laboratories for Materials Science and Technology (EMPA) (Weber and Dorer, 2008).

The pair NaOH/H_2O was studied by Weber and Dorer (2008) using a single-stage closed absorption prototype for long-term heat storage. The prototype built has three storage tanks for water, strong solution, and weak solution (Figure 7.20).

Based on a three-phase absorption cycle, ClimateWell (Jonsson et al., 2000; Bolin, 2005; Olsson and Bolin, 2007) developed a system combining short-term absorption thermal storage and solar cooling technologies. The tests carried out showed that with a 35 kWh heat input, a cooling storage capacity of 22 kWh could be obtained. The calculated energy density for LiCl was 253 kWh m^3, giving a final energy density 1.2 times that of water.

Quinnell et al. (2011) and Quinnell and Davidson (2012) presented a concept using a single storage vessel for storing liquid calcium chloride in a closed liquid absorption system. The storage tank in this prototype is designed to provide higher energy density and to decrease thermal losses during the storage process (Figure 7.21).

A demonstrative LiBr/H_2O prototype with a heat storage capacity of 8 kWh and a discharge rate of 1 kW has recently been developed by N'Tsoukpoe et al. (2013) (Figure 7.22). The prototype is based on a long-term absorption storage cycle and has two storage tanks and a reactor with two vertical falling-film heat exchangers. The achieved charging power was 2−5 kW and the heat storage up to 13 kWh. As in previous prototypes, crystallization of the salts was the main problem found.

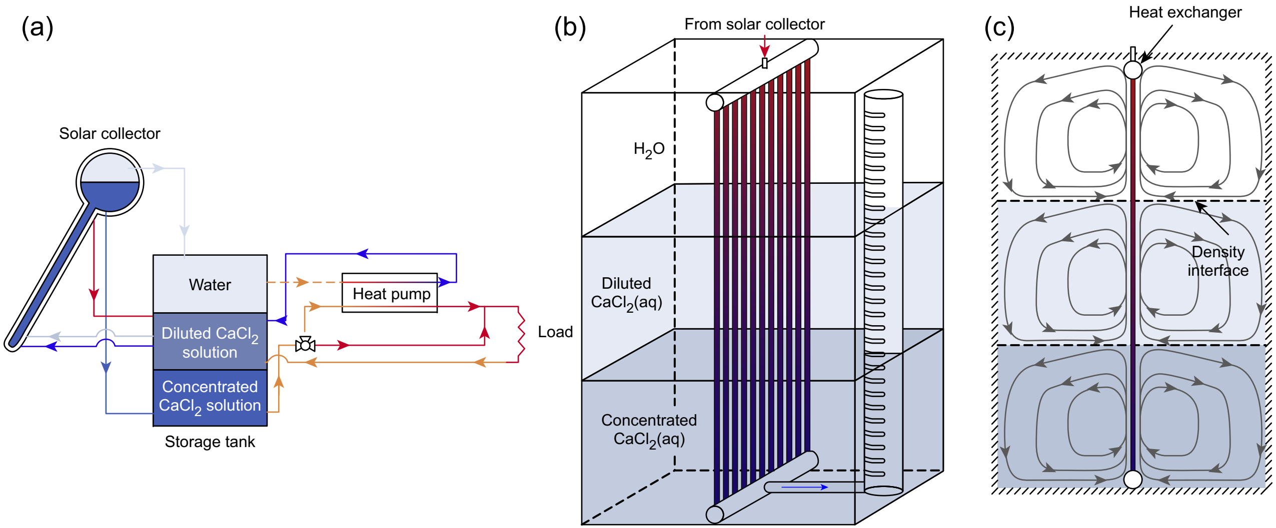


Figure 7.21 Closed $CaCl_2/H_2O$ absorption heating system with a single-store vessel: (a) system schematic (Quinnell and Davidson, 2012); (b) storage tank schematic (Quinnell et al., 2011); (c) anticipated convective flow patterns during sensible charging (Quinnell et al., 2011).

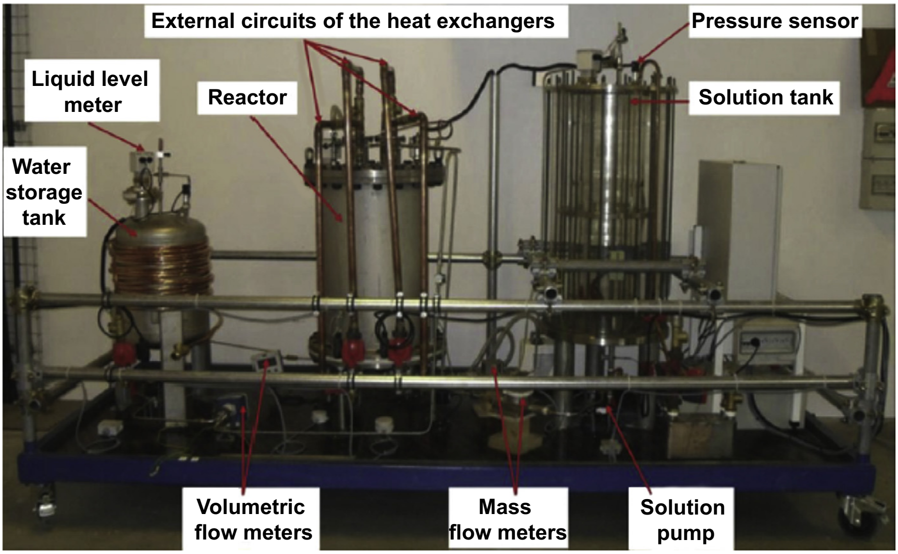


Figure 7.22 LiBr/H_2O absorption prototype developed by N'Tsoukpoe et al. (2013).

The prototype MODESTORE used the positive points of the pair silica gel/H_2O, such as being environmentally harmless and relatively cheap and having low desorption temperatures (Figure 7.23). This prototype used a spiral heat exchanger containing 200 kg of silica gel (Jaenig et al., 2006). The storage capacity obtained in the laboratory was 13 kW. The authors concluded that silica gel is not suitable for long-term sorption TES.

Lu et al. (2003) used a closed-adsorption cold-storage system with the working pair zeolite 13X/water. This prototype has one adsorber and a cold-storage tank (Figure 7.24). The average cooling power reported is 4.1 kW, and the total experimental capacity of the cold storage 5.5 kWh when the temperature of adsorption bed reached its maximum value of 125 °C.

Boer et al. (2004) developed the SWEAT prototype of a modular chemical adsorption cooling system using the working pair Na_2S/H_2O (Figure 7.25). The module has a shell and tube design, a condenser, and an evaporator coil. The test results showed that a cold storage capacity of 2.1 kWh and a cooling COP of 0.56 were achieved with a heat input of 3.7 kWh.

Mauran et al. (2008) presented a storage prototype using the reversible chemical reaction between $SrBr_2$ and $SrBr_2 \cdot H_2O$. The reactor integrated an evaporator/condenser for the solid—gas reaction. The heating and cooling power obtained proved that the most challenging feature that needs to be overcome in this type of concept is the heat transfer problem encountered.

A solar air-conditioning pilot plant with a daily cooling capacity of 20 kWh with a working pair of $BaCl_2/NH_2$ was presented by Stitou et al. (2011) (Figure 7.26). The heat input is at 60 to 70 °C from 20 m^2 of flat-plate solar collectors. Along with

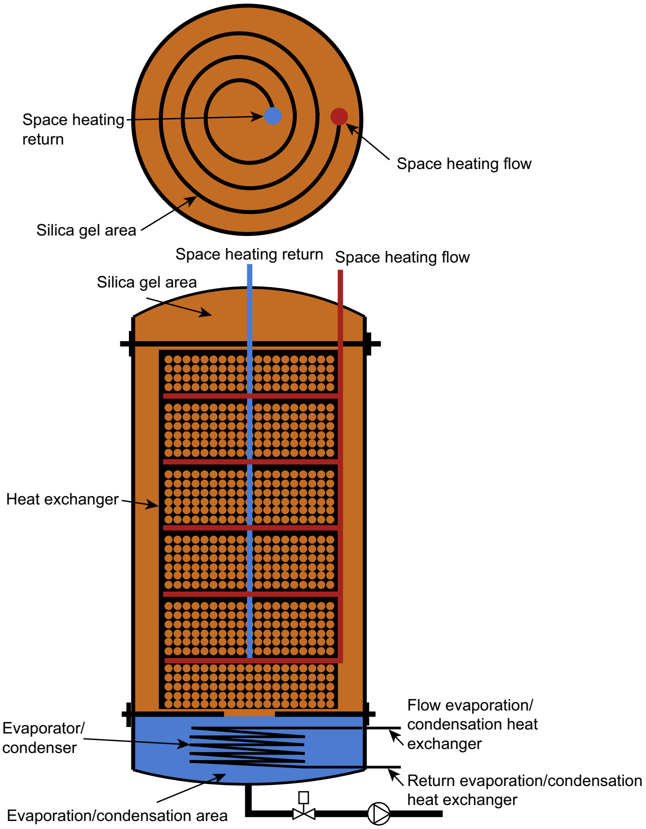


Figure 7.23 MODESTORE prototype (Jaenig et al., 2006).

Mauran et al. (2008), this prototype includes expanded graphite in the design to improve the heat transfer. The prototype also includes a hot PCM tank to store the excess solar heat and a cold PCM tank to supply cooling when the sorption reaction is not available. Experiments during 2 years showed an average yearly efficiency of solar collectors of 0.4 to 0.5 and COP of 0.3 to 0.4. The daily storage capacity was about 0.8−1.2 kWh m^{-2} plate solar collector at 4 °C.

The ZAE Bayern installed a large-scale open-adsorption TES using zeolite 13X/water to heat a school building in winter and to cool a jazz club in summer in Munich (Hauer, 2002, 2007). Figure 7.27 shows the heat flux during charging and discharging. The prototype obtained storage densities of 124 kWh m^{-3} for heating and 100 kWh m^{-3} for cooling with a COP of 0.9 and 0.86, respectively.

Another design is that named chemical heat transfer−low temperature (CWT-NT) (Kerkes et al., 2011; Kerskes et al., 2012; Metter et al., 2013). This concept consists of a long-term thermochemical energy storage integrated in a solar thermal combisystem for a composite of zeolite and salt (Figure 7.28). The system is designed as an open system using ambient air for charging and discharging.

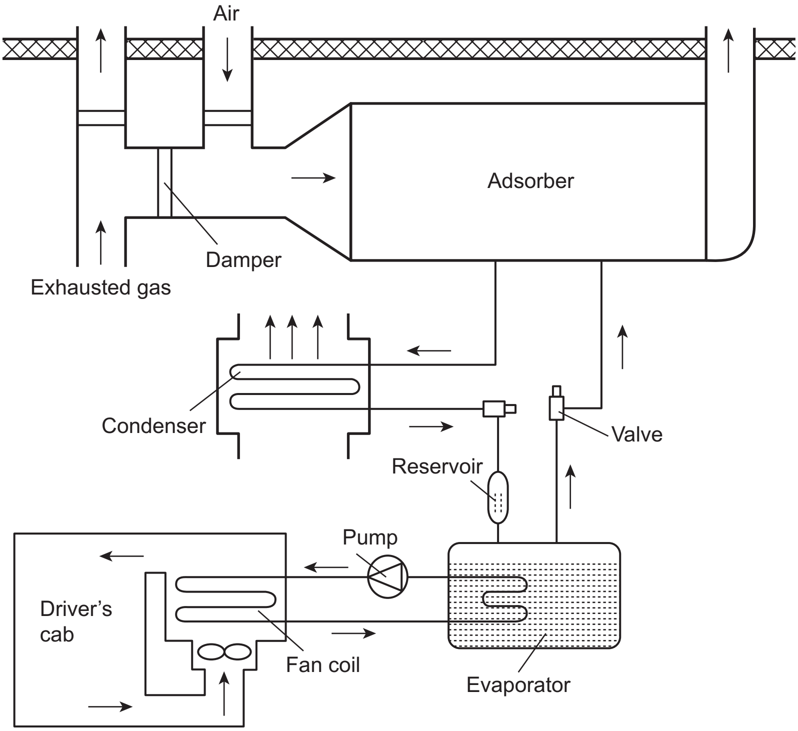


Figure 7.24 Zeolite/water adsorption cold storage system (Lu et al., 2003).

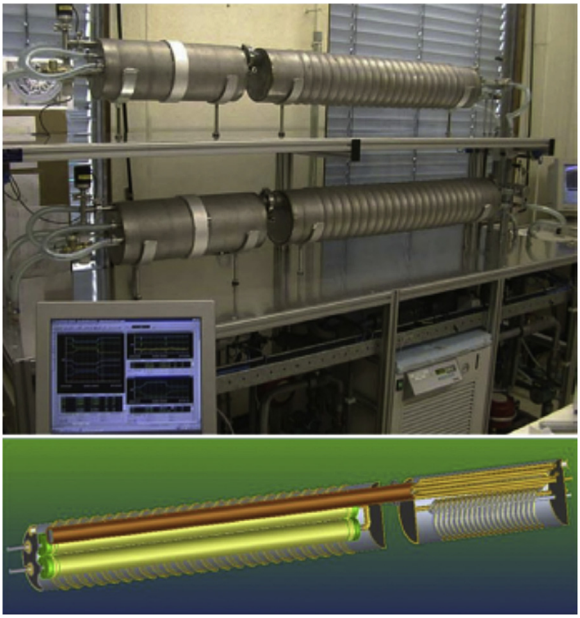


Figure 7.25 SWEAT storage concept (Boer et al., 2004).

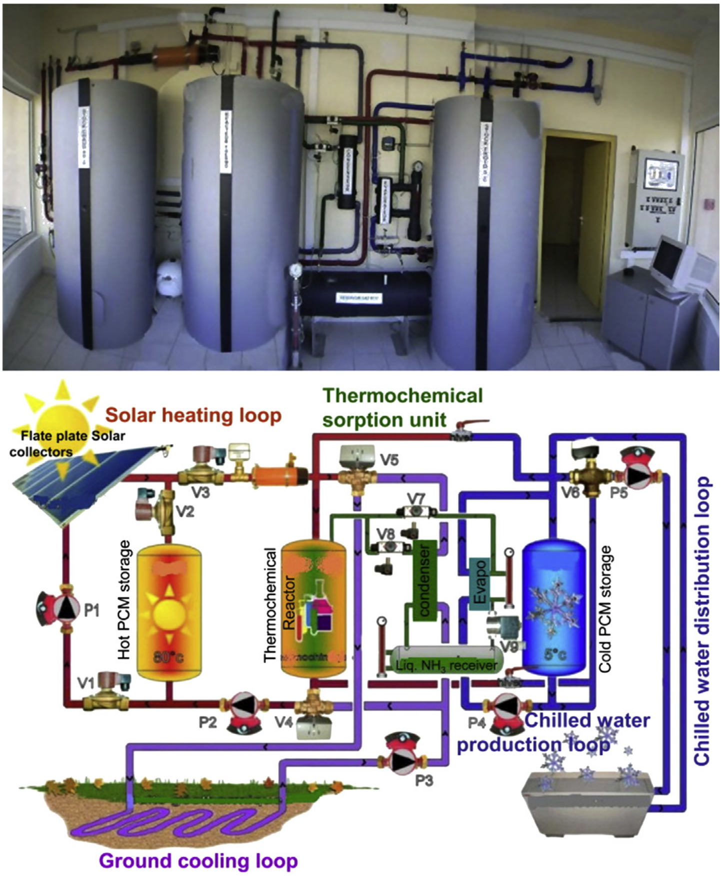


Figure 7.26 Solar sorption pilot plant for air conditioning (Stitou et al., 2011).

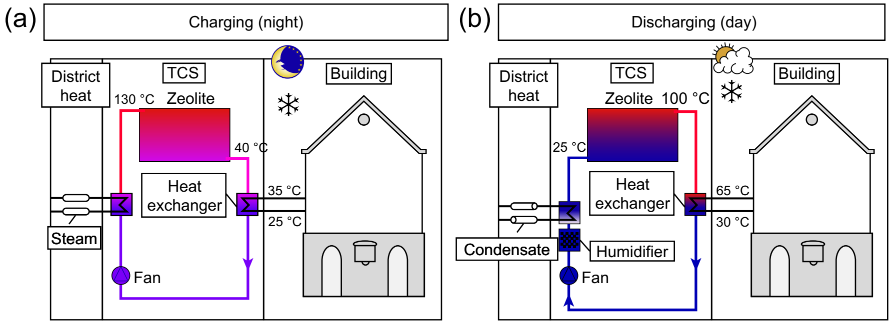


Figure 7.27 Open adsorption TES system connected to the district heating system in Munich (Hauer, 2002).

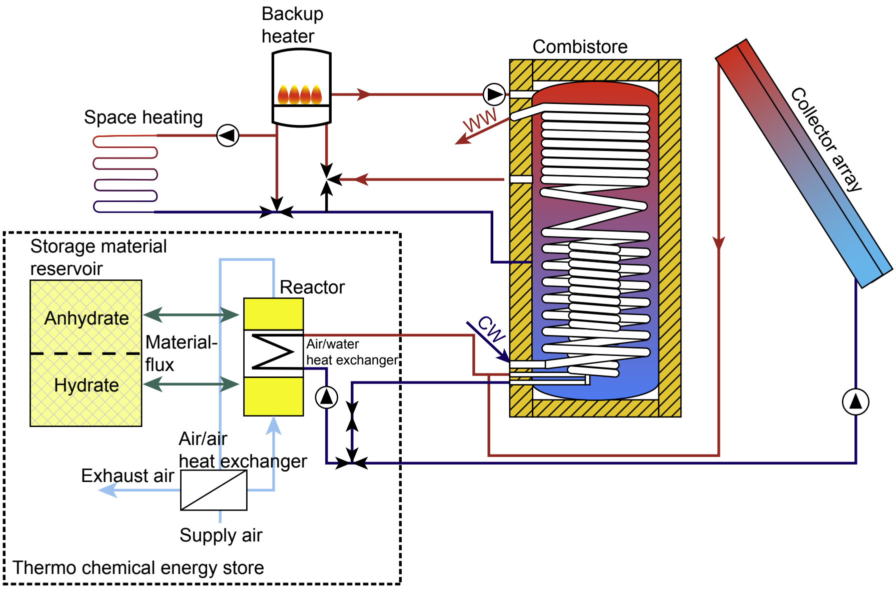


Figure 7.28 CWT-NT concept schematics (Kerskes et al., 2012).

7.2.3 Seasonal storage

7.2.3.1 Underground thermal energy storage

Underground thermal energy storage (UTES) with both boreholes (BTES) and aquifers (ATES) are the most developed storage concepts and are mostly used for seasonal storage. The description of the concepts can be found in Paksoy (2007) and Mehling and Cabeza (2008).

Heat storage in ATES consists in extracting groundwater from a well, heating this water with an available heat source, and then reinjecting it back into the aquifer in another well. The estimated heat storage capacity of 10^5 m^3 of aquifer is 3 MJ for each 10 K temperature range (Hasnain, 1998).

7.2.3.2 Water pits and solar ponds

Novo et al. (2010) reviewed TES systems in large basins (water tanks and gravel—water pits). These authors claimed that the energy costs can be reduced with increasing storage volume in large-scale solar applications.

The most common use of water tanks in Europe is in connection with solar collectors for production of warm water for space heating and/or DHW. The main application is in smaller solar plants such as described above, but there are some examples of large water tanks being used for seasonal storage and also used as a buffer storage in connection with large-scale solar heating systems.

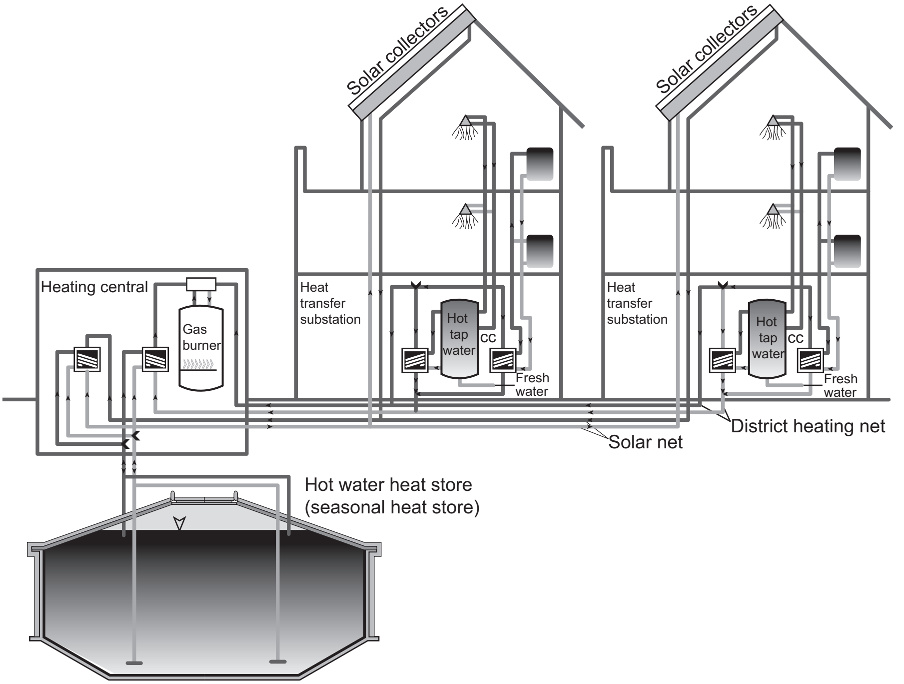


Figure 7.29 Scheme of the system installed in Friedrichshafen, Germany (Schmidt et al., 2004).

These large water tanks usually consist of a reinforced concrete tank partially buried in the ground. It is thermally insulated at least in the roof area and on the vertical walls. Usually steel liners are introduced in the structure to guarantee water tightness and to reduce heat losses caused by vapor transport through the walls (Schmidt et al., 2004). Such a system was installed in Germany (Figure 7.29) together with other concepts.

Storage pits are usually filled with water, but sometimes also rock is added in the pit. Pits are normally buried in the ground and need to be waterproofed and insulated at least at the side walls and on the top. The watertight plastic liner is filled with a gravel—water mixture that constitutes the storage material. Heat is charged into and discharged out of the store either by direct water exchange or by plastic piping installed in different layers inside the store. No other bearing structure is necessary apart from the cover (lid) that could be used for other purposes. The gravel—water mixture has lower specific heat capacity than water alone; for this reason, the volume of the whole basin has to be approximately 50% higher compared to hot-water heat storage to obtain the same heat storage capacity.

Solar ponds are large volumes of saline solution with higher concentration of salts at the bottom than at the top (Figure 7.30). Solar ponds are an economical method to collect and store solar thermal energy in the temperature range 50—95 °C (Novo et al., 2010).

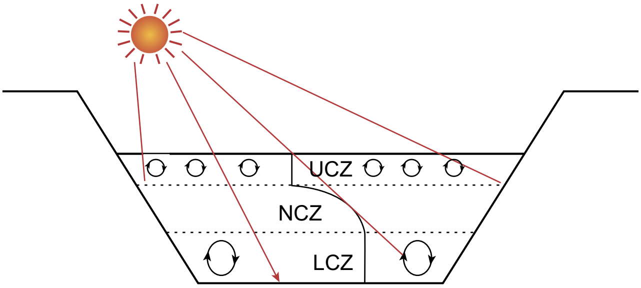


Figure 7.30 Schematic of a solar pond (UCZ = upper convective zone; NCZ = nonconvective zone; LCZ = lower convective zone) (Tatsikjoudoung et al., 2013).

Novo et al. (2010) presented a comparison of these storage systems, stating that the gravel–water pit technology can reduce construction costs and the upper part of the store can be used as part of the residential area but needs more volume to store the same thermal energy than a water tank design. The demonstration sites carried out showed that solar collector efficiency and heat losses from the storage tank and the piping network are most important.

7.2.3.3 Thermochemical storage

Most of the concepts presented in Section 7.2.2.2 as sorption systems are being further developed today for seasonal storage.

7.3 R&D needs and future trends in technological development, markets, and applications

The R&D needs have been captured by the European Technology Platform on Renewable Heating and Cooling (RHC Platform—www.rhc-platform.org) Strategic Research Priorities (Axel et al., 2012). The RHC Platform claims that the emphasis of scientific research, development, and demonstration activities must be focused toward storage technologies that enhance the performance of energy systems and facilitate the integration of renewable energy systems in buildings. Table 7.6 presents the strategic and research priorities for TES according to the RHC Platform.

Because many technologies exist at laboratory scale, the future of TES applications depends on the reduction of costs and improving the ability to efficiently shift energy demand over days, weeks, or seasons. To achieve these objectives, efforts should be focused on advanced sensible heat storage, PCMs, sorption, and thermochemical methods. The most promising areas of research are in latent heat storage and novel thermochemical concepts. Decentralized systems and stores connected to the district heating and cooling networks have potential, so both must be considered.

Table 7.6 **Strategic and research priorities for TES according to the RHC platform (Axel et al., 2012)**

	Basic research	Applied R&D	Demonstration
Sensible TES	• Materials research for the reduction of heat losses • Materials research for high-temperature storage with high thermal conductivity • Fluids combining heat transfer and heat storage	• Microbiology in underground thermal energy storage (UTES) systems • Flexible volume tank systems • Development of new methods of TES materials' analysis	• Optimization of hydraulics in advanced water stores, reduction of mixing, and increased stratification • Control strategies for integrating sensible stores into the smart grid • High-temperature underground storage (HT-UTES)
Latent TES	• Optimization of phase change heat storage • Fluids combining heat transfer and heat storage	• Integration of phase change materials in building elements	• Software algorithms and codes for ERBP enabling software packages
Thermochemical storage	• Materials for thermochemical heat storage • Fluids combining heat transfer and heat storage	• Optimization of thermochemical heat storage processes • High-temperature thermochemical systems	
Research priorities at system level	• Materials for storage containment	• Advanced sensoring in storage systems • Distributed thermal energy storage for smart electricity grids in smart cities	• Optimized integration of UTES systems • Advanced control strategies • Storage of rejection heat in solar cooling processed and solar power plants • System evaluation
Nontechnological priorities	• Education and training • Knowledge of system performance • Labeling or certification of TES devices • Legal framework UTES (ATES/BTES) • Public awareness		

Another topic is the improvement of the properties of TES materials, especially in improving the lifetime chemical and physical stability. The durability of new systems and their parts also needs to be assessed to ensure their long-term performance.

According to Mahlia et al. (2014), there are three key barriers for the deployment of the energy storage technology, regulations, and utility processes that disfavor energy storage, costs, and lack of awareness of energy storage benefits. These three barriers can also be applied to TES. Important is the fact that there is no experience in deploying energy storage at large scale, so policymakers lack conclusive data about the costs and energy savings capacity of TES.

Sources of further information and advice

Further information on the topic can be found in the published books such as Dincer and Rosen (2002), Hadorn (2005), Paksoy (2007), Mehling and Cabeza (2008), and a chapter in Cabeza (2012).

Many reviews have been published on the topic: Zalba et al. (2003), Farid et al. (2004), Kenisarin and Mahkamov (2007). Sharma et al. (2009), Gil et al. (2010), Cabeza et al. (2011), Cot-Gores et al. (2012), Rathod and Banerjee (2013), and Soares et al. (2013).

Important is the work developed within the International Energy Agency Implementing Agreements. Worth mentioning are Energy Conservation through Energy Storage IA (ECES IA—www.iea-eces.org) and the Solar Heating and Cooling IA (SHC Program—www.iea-shc.org).

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