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Thermal energy storage: - A review

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Abstract: *Developing efficient and inexpensive energy storage devices is as important as developing new sources of energy. Thermal energy storage in the three forms viz. sensible heat storage, Latent heat storage with phase change materials, and thermo chemical energy storage is discussed in details. Several works pertaining to these methods are reviewed to understand the technological as well as economic factors. Materials (both liquids and solids) used for sensible heat storage are discussed and analyzed. Prospective materials that may be used as phase change materials are also tabulated. Finally the challenges ahead for thermal energy storage are also discussed.*

Key words*: Thermal energy storage (TES), sensible heat storage (SHS) , Latent heat storage (LHS) Phase change Materials (PCM)*

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I. Introduction

The thermal energy storage (TES) can be defined as the temporary storage of thermal energy at high or low temperatures. Energy storage can reduce the time or rate mismatch between energy supply and energy demand, and it plays an important role in energy conservation. It is a technology that stores thermal energy by heating or cooling a storage medium so that the stored energy can be used at a later time as per requirement for heating and cooling applications and power generation.

Thermal energy storage systems can be either centralized or distributed systems. Centralized applications can be used in district heating or cooling systems, large industrial plants, combined heat and power plants, or in renewable power plants. Distributed systems are mostly applied in domestic or commercial buildings to capture solar energy for water and space heating or cooling. In both cases, TES systems may reduce energy demand at peak times. A TES system's economic performance depends substantially on its specific application and operational needs, including the number and frequency of storage cycles. In general, PCM and TCS systems are more expensive than sensible heat systems and are economically viable only for applications with a high number of cycles. In developed countries, a major constraint for TES deployment is the low construction rate of new buildings, while in emerging economies TES systems has a larger deployment potential. TES systems are used particularly in buildings and industrial processes. In these applications, approximately half of the energy consumed is in the form of thermal energy, the demand for which may vary during any given day and from one day to next. Therefore, TES systems can help balance energy demand and supply on a daily, weekly and even seasonal basis. They can also reduce peak demand, energy consumption, CO_2 emissions and costs, while increasing overall efficiency of energy systems. Furthermore, the conversion and storage of variable renewable energy in the form of thermal energy can also help increase the share of renewable energy in the energy mix. TES is becoming particularly important for electricity storage in combination with concentrating solar power plants where solar heat can be stored for electricity production when sunlight is not available.

Energy storage not only reduces the mismatch between supply and demand but also improves the performance and reliability of energy systems and plays an important role in conserving the energy [1, 2]. It leads to saving of premium fuels and makes the system more cost effective by reducing the wastage of energy and capital cost. For example, storage would improve the performance of a power generation plant by load leveling and higher efficiency would lead to energy conservation and lesser generation cost. One of prospective techniques of storing thermal energy is the application of phase change materials (PCMs). Unfortunately, prior to the large-scale practical application of this technology, it is necessary to resolve numerous problems at the research and development stage. Types of energy storage methods are given below.

If mass specific heat capacity is not small, denser materials have smaller volumes and correspondingly an advantage of larger energy capacity per unit volume. The space available is limited both in transport and in habitat applications. The volume occupied by the present available storage systems is considerable and may be an important factor in limiting the size of storage provided. The amount of energy storage provided is dictated by the cost. The cost of floor space or volumetric space should be one of the parameters in optimizing the size of storage.

The technology of thermal energy storage has been developed to a point where it can have a significant effect on modern life. The major nontechnical use of thermal storage was to maintain a constant temperature in dwelling, to keep it warm during cold winter nights. Large stones, blocks of cast iron, and ceramics were used to store heat from an evening fire for the entire night. With the advent of the industrial revolution, thermal energy storage introduced as a by-product of the energy production. A variety of new techniques of thermal energy storage have become possible in the past. A major application for thermal storage today is in family dwellings. Heat storage at power plants typically is in the form of steam or hot water and is usually for a short time.

Very recently other materials such as oils having very high boiling point, have been suggested as heat storage substances for the electric utilities. Other materials that have a high heat of fusion at high temperatures have also been suggested for this application. Another application of thermal energy storage on the electric utilities is to provide hot water. Perhaps the most promising application of thermal energy storage is for solar heated structures, and almost any material can be used for thermal energy storage.

There are three kinds of TES systems, namely: 1) sensible heat storage that is based on storing thermal energy by heating or cooling a liquid or solid storage medium (e.g. water, sand, molten salts, rocks); 2) thermo-chemical storage (TCS) using chemical reactions to store and release thermal energy. 3) Latent heat storage using phase change materials or PCMs (e.g. from a solid state into a liquid state).

Table 1 A typical comparison of thermal energy storage systems (3)

TES	**Capacity**	**Power**	**Efficiency**	**Storage period**	**Cost**
System	(kWh/t)	MW)	(%)	(h, d, m)	(€/kWh)
Sensible (hot water)	10--50	0.001-10	50-90	d/m	0.1-10
PCM	50-150	0.001-1	75-90	h/m	10--50
Chemical reactions	120-250	0.01-1	75-100	h/d	8-100

II. Sensible Heat Storage

Heating a liquid or a solid, without changing phase: This method is called sensible heat storage. Sensible heat storage is relatively inexpensive compared to PCM and TCS systems and is applicable to domestic systems, district heating and industrial needs. However, in general sensible heat storage requires large volumes because of its low energy density (i.e. three and five times lower than that of PCM and TCS systems, respectively). Furthermore, sensible heat storage systems require proper design to discharge thermal energy at constant temperatures. Several developers in Germany, Slovenia, Japan, Russia and the Netherlands are working on new materials and techniques for all TES systems, including their integration into building walls (e.g. by encapsulating phase change materials into plaster or air vents) and transportation of thermal energy from one place to another. These new applications are just now being commercialized, and their cost, performance and reliability need to be verified.

The choice of the substance used depends largely on the temperature level of the application, water being used for temperature below 100°C and refractory bricks being used for temperatures around 1000°C. Sensible heat storage systems are simpler in design than latent heat or bond storage systems. However they suffer from the disadvantage of being bigger in size. For this reason, an important criterion in selecting a material for sensible heat storage is its density and specific heating value. A second disadvantage associated with sensible heat systems is that they cannot store or deliver energy at a constant temperature

2.1 Liquids as medium of heat storage

A variety of substances have been used in such systems. These include liquids like water, heat transfer oils and certain inorganic molten salts, and solid like rocks, pebbles and refractory (4).

Table 2: Properties of Liquid Media for Sensible Heat Storage.

Medium	Fluid Type	Temp. Range (°C)	Density Kg/m^3	Heat Capacity (J/kg.K)	Thermal Conductivity (W/m.K)
Water	-	0 to 100	1000	4190	0.63 at 38°C
Water-Ethylene Glycol 50/50	-	-	1050	3470	-
Caloria HT43	Oil	-10 to 315	-	2300	-

Dowtherms	Oil	12 to 260	867	2200	0.112 at 260°C
Therminol 55	Oil	-18 to 315	-	2400	-
Therminol 66	Oil	-9 to 343	750	2100	0.106 at 343
Ethylene Glycol	-	-	1116	2382	0.249 at 20°C
Hitec	Molten salt	141 to 540	1680	1560	0.61
Engine oil	Oil	Up to 160	888	1880	0.145
Draw salt	Molten salt	220 to 540	1733	1550	0.57
Lithium	Liquid salt	180 to 1300	510	4190	38.1
Sodium	Liquid salt	100 to 760	960	1300	67.5
Ethanol	Organic liquid	Up to 78	790	2400	-
Propanol	- do -	Up to 97	800	2500	-
Butanol	- do -	Up to 118	809	2400	-
Isobuthanol	- do -	Up to 100	808	3000	-
Isopentanol	- do -	Up to 148	831	2200	-
Octane	- do -	Up to 126	704	2400	-

With its highest specific heat water is the most commonly used medium in a sensible heat storage system. Most solar water heating and space-heating systems use hot water storage tanks located either inside or outside the buildings or underground. The sizes of the tanks used vary from a few hundred liters to a few thousand cubic meters. An approximate thumb rule followed for fixing the size is to use about 75 to 100 liters of storage per square meter of collector area.

Water storage tanks are made from a variety of materials like steel, concrete and fiberglass. The tanks are suitably insulated with glass wool, mineral wool or polyurethane. The thickness of insulation used is large and ranges from 10 to 20 cm. because of this, the cost of the insulation represents a significant part of the total cost and mean to reduce this cost have to be explored. Shelton has shown that in an underground tank, the insulating value of the earth surrounding the tank may be adequate and this could provide the bulk of the insulation thickness required. However, it may take as much as one year for the earth around a large storage tank to reach a steady state by heating and drying, and a considerable amount of energy may be required for this purpose. If the water is at atmospheric pressure, the temperature is limited to 100°C. It is possible to store water at temperature a little above 100°C by using pressurized tanks. This has been done in a few instances.

Heat transfer oils are used in sensible heat storage systems for intermediate temperatures ranging from 100 to 300 °C. Some of the heat transfer oils used for this purpose are Dowtherm and Therminol. The problem associated with the use of heat transfer oils is that they tend to degrade with time. The degradation is particularly serious if they are used above their recommended temperature limit. The use of oils also presents safety problems since there is a possibility of ignition above their flash point. For this reason, it is recommended that they be used in systems with an inert gas cover. A further limitation to the use of heat transfer oils is their cost. For this reason, they can be seriously considered for use only in small storage systems. A few molten inorganic salts have been considered for high temperatures (300°C and above). One is an eutectic mixture of 40 percent NaNO2, 7 percent NaNO3 and 53 percent KNO2 (by weight) and is available under the trade name of 'Hitec'. Hitec has a low melting point of 145°C and can be used up to a temperature of 425°C. Above this temperature; decomposition and oxidation begin to take place. Another molten salt being considered for high temperature storage is sodium hydroxide, which has a melting point of 320°C and could be used for temperatures up to 800°C. However, it is highly corrosive and there is difficulty in containing it at higher temperatures. Water, being inexpensive and widely available can be effectively used to store sensible heat.

The advantages and disadvantages of such storage can be summarized as follows:

Advantages:
1. Water is inexpensive, easy to handle, non-toxic, non-combustible and widely available.
2. Water has a comparatively high specific heat and high density
3. Heat exchangers may be avoided if water is used as the heat carrier in the collector.
4. Natural convection flows can be utilized when pumping energy is scarce.
5. Simultaneous charging and discharging of the storage tank is possible.
6. Adjustment and control of a water system is variable and flexible.

Disadvantages:
1. Water might freeze or boil
2. Water is highly corrosive
3. Working temperatures are limited to less than 100°C and often have to be far below this boiling temperature.
4. Water is difficult to stratify.

Freezing and corrosion problems can be met by using chemical additives. Water sometimes remains economically competitive at higher temperatures despite the need for pressure containment especially so when it is stored in aquifers. Organic oils, molten salts, and liquid metals circumvent the problems of vapor pressure, but have other limitations in handling, containment, cost, storage capacities, useful temperature range, etc. In spite of the fact that these fluids have been used in commercial operations, the lifetime and cost requirements for solar thermal storage limit their use in applications such as space heating. However, oils and molten salts have been utilized in solar thermal power plants

2.2 Sensible energy storage in anhydrous molten salts/nitrates

For sensible heat storage at elevated temperatures ($T > 100$ °C) molten salts are most suitable. Advantages of molten salts are the high thermal stability, relatively low material costs, high heat capacity, high density, non-flammability and low vapor pressure. Due to the low vapor pressure pressurized vessels are not required.

Compared to organic heat transfer fluids the melting point of molten salts is higher. Thus one major challenge with molten salts is to avoid freezing during operation. Hence, typically auxiliary heating systems or the development of salt formulations with low melting temperatures are required. A novel method to identify the composition of salt mixtures featuring a decreased melting temperature is presented at the end of this section. Additionally limitations of molten salt storage may arise due to storage media costs, the risk of corrosion and the difficulty in hygroscopic salt handling.

For sensible heat storage in solar power plants, a non-eutectic molten salt mixture consisting of 60 wt % sodium nitrate ($NaNO_3$) and 40 wt % potassium nitrate (KNO_3) is used. This mixture is usually known as "Solar Salt". Due to the increased amount of $NaNO_3$ as compared to the eutectic mixture the material costs can be reduced. The non-eutectic mixture has a liquidus temperature of about 240 °C and the temperature limit of thermal stability is about 550 °C. For applications at higher temperatures salts with other anions, such as carbonates, chlorides and fluorides might be potential candidates. However experience with oxyanion salts and halogen salts is currently limited to theoretical studies [5-6].

Typical picture of different types of salts used as **sensible liquid Heat Storage Materials is shown in Fig. 1**

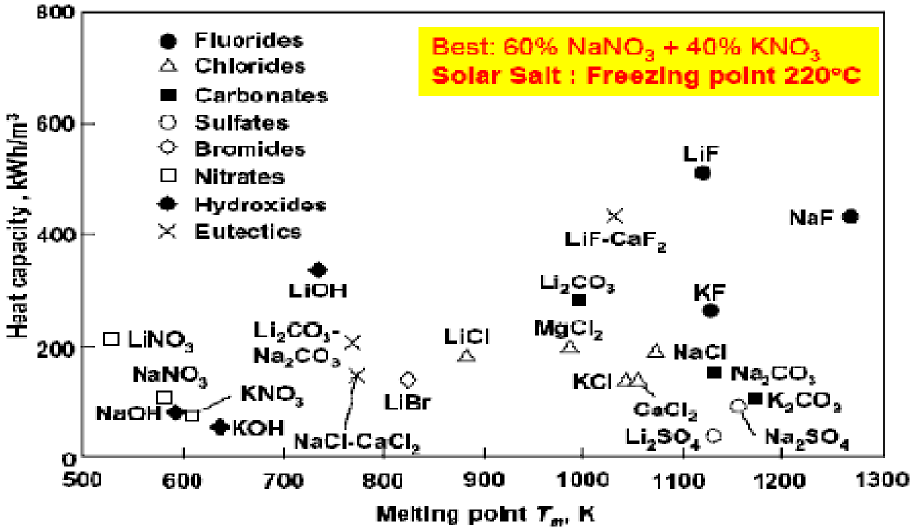

Fig 1. Molten Salts (Sensible liquid Heat Storage Materials) (7)

2.3 Various other methods of sensible energy storage are also being considered as follows

2.3.1 Underground Thermal Energy Storage (UTES) –

UTES is also a widely used storage technology, which makes use of the underground as a storage medium for both heat and cold storage. UTES technologies include borehole storage, aquifer storage, cavern storage and pit storage. Which of these technologies is selected strongly depends on the local geological conditions.

2.3.2 Borehole storage

It is based on vertical heat exchangers installed underground, which ensure the transfer of thermal energy to and from the ground layers (e.g. clay, sand, rock). Many projects aim for seasonal storage of solar heat in summer to heat houses or offices in winter. Ground heat exchangers are also frequently used in combination with heat pumps where the ground heat exchanger extracts low-temperature heat from the soil.

2.3.3 Aquifer storage

It uses a natural underground water-permeable layer as a storage medium. The transfer of thermal energy is achieved by mass transfer (i.e. extracting/re-injecting water from/into the underground layer). Most applications deal with the storage of winter cold to be used for the cooling of large office buildings and industrial processes in the summer. A major prerequisite for this technology is the availability of suitable geological formations.

2.3.4 Cavern storage and pit storage

It is based on large underground water reservoirs created in the subsoil to serve as thermal energy storage systems. These storage options are technically feasible, but applications are limited because of the high investment costs. For high-temperature (i.e. above 100 °C) sensible heat storage, the technology of choice is based on the use of liquids (e.g. oil or molten salts, the latter for temperatures up to 550°C. For very high temperatures, solid materials (e.g. ceramics, concrete) are also taken into consideration. However, most of such high-temperature-sensible TES options are still under development or demonstration.

III. Latent Heat Storage

Latent heat storage (LHS) is based on the heat absorption or release when a storage material undergoes a phase change from solid to liquid or liquid to gas or vice versa. In latent heat storage the principle is that when heat is applied to the material it changes its phase from solid to liquid by storing the heat as latent heat of fusion or from liquid to vapor as latent heat of vaporization. When the stored heat is extracted by the load, the material will again change its phase from liquid to solid or from vapor to liquid. The latent heat of transformation from one solid phase into another is small. Solid-vapor and liquid-vapor transitions have large amounts of heat of transformation, but large changes in volume make the system complex and impractical. The solid-liquid transformations involve relatively small changes in volume. Such materials are available in a range of transition temperatures.

Sensible heat storage is relatively inexpensive, but its drawbacks are its low energy density and its variable discharging temperature [8]. These issues can be overcome by phase change materials (PCM)-based TES, which enables higher storage capacities and target oriented discharging temperatures. The change of phase could be either a solid/liquid or a solid/solid process. Melting processes involve energy densities on the order of 100 kWh/m3 (e.g. ice) compared to a typical 25 kWh/m3 for sensible heat storage options. Figure 3 compares the achievable storage capacity at a given temperature difference for a storage medium with and without phase change.

Phase change materials can be used for both short-term (daily) and long term (seasonal) energy storage, using a variety of techniques and materials. For example, the incorporation of micro-encapsulated PCM materials (e.g. paraffin wax) into gypsum walls or plaster can considerably increase the thermal mass and capacity of lightweight building walls. The micro-encapsulated PCMs cool and solidify by night and melt during the day, thus cooling the walls and reducing or avoiding the need for electric chillers. Other applications for active cooling systems involve the use of macro-encapsulated salts that melt at an appropriate temperature. The PCM can be stored in the building's air vent ducts and cold air can be delivered via large-area ceiling and floor ventilation systems. PCM slurries are a promising technology. For example, ice-slurries or water-paraffin dispersions can be used for building or industrial cooling purposes. As slurries can be pumped, they can be used for either storing or distributing thermal energy.

Heat storage through phase change has the advantage of compactness, since the latent heat of fusion of most materials is very much larger than their enthalpy change for 1 K or even 0^0 K. For example, the ratio of latent heat to specific heat of water is 80, which means that the energy required to melt one kilogram of ice is 80 times more than that required to raise the temperature of one kilogram of water one degree Celsius.

Furthermore, the PCMs undergo solidification and therefore cannot generally be used as heat transfer media in a solar collector or the load. Many PCMs have poor thermal conductivity and therefore require large heat exchange area. Others are corrosive and require special containers. Latent heat storage materials are more expensive than the sensible heat storage media generally employed, like water and rocks. These increase the system cost.

Due to its high cost, latent heat storage is more likely to find application when:

1. High energy density or high volumetric energy capacity is desired, e.g., in habitat where space is at a premium, or in transportation where both volume or weight must be kept to a minimum,
2. The load is such that energy is required at a constant temperature or within a small range of temperatures, or
3. The storage size is small. Smaller storage has higher surface area to volume ratio and therefore cost of packing is high. Compactness is then very important in order to limit the containment costs. Similarly, heat losses are also more or less proportional to the surface area. Compactness is also an important factor to limit the heat losses in storages of small capacities.

3.1 Classification of Phase Change Materials (PCMs)

Phase Changing Materials can be classified into the following types based on their composition
1.Organic PCMs 2.Inorganic PCMs 3.Eutectics PCMs
The classification of PCM based on their composition [9, 10] is as listed in Table 2.

Table 2. Classification of PCM

PCM Type	Composition
ORGANIC	Paraffin Compounds Compounds without paraffin
INORGANIC	Hydrated salts, Metallic
EUTECTICS	Organic-organic Organic-inorganic Inorganic-inorganic

Based on the size of capsules PCM's can be classified into the following two types
Micro PCMs and Macro PCMs

3.1.1 Organic PCMs

Organic materials melt and freeze without degradation and segregation and possess the property of self-nucleation. Organic PCM's are further classified into paraffins and non-paraffins.

3.1.1.1 Paraffins

Paraffins are made up of mixtures of n-alkanes. The heat is released by crystallization of these alkane chains. As the chain length increases the latent heat of fusion and melting point increases. Paraffins are dependable and cheap. Systems employing them have very long freeze and melt cycles. However they possess some undesirable properties such as low thermal conductivity and flammability. Such undesirable properties can be eliminated by modifying the wax contents. Paraffin waxes are the most common PCM for electronics thermal management because they have a high heat of fusion per unit weight, have a large melting point selection, provide dependable cycling, are non-corrosive and are chemically inert. When designing with paraffin PCM, void management is important due to the volume change from solid to liquid. Paraffin PCM's also have a low thermal conductivity, so designing sufficient conduction paths is another key design consideration.

3.1.1.2 Non paraffins

Unlike paraffins each of the materials belonging to the category of non-paraffins has different properties. They outweigh paraffins in number. They are available in large numbers. The features of these non paraffins include high heat of fusion, low thermal conductivity, toxicity and instability at higher temperatures. Micro encapsulation and macro encapsulation of phase change materials are the two processes which split them into micro and macro PCMs.

3.1.2 Inorganic PCMs

Inorganic PCMs do not supercool to the required levels and there is no degradation of heat of fusion. Inoganic PCMs are further classified in to salt hydrates and metallics.

3.1.2.1 Salt hydrates

The general formula of salt hydrates is $AB.nH_2O$.The most attractive properties of salt hydrates include high latent heat of fusion, high thermal conductivity and small volume changes. They are non-corrosive and non-toxic. The major problem in using salt hydrates is congruent melting. The problem of congruent melting can be overcome by mechanical stirring, encapsulation, adding thickness agents and water and by modifying the chemical composition of the system. Hydrated salts are another category. These PCM's have a high heat of fusion per unit weight and volume, have a relatively high thermal conductivity for non-metals, and show small volume changes between solid and liquid phases. These are not commonly used for electronics heat sinks, since they are corrosive and long term reliability (thousands of cycles) is uncertain. The most common application is for very large thermal storage applications (e.g., solar heating), where there much lower cost is very attractive.

3.1.2.2. Metallics

Low melting metals form the subclass of metallics. However the usage of metallics is limited except in the case of low volume applications.

3.1.3 .Eutectics

A eutectic is a minimum-melting composition of two or more components, each of which melts and freeze congruently forming a mixture of the component crystals during crystallization [11]. Eutectic nearly melts and freezes without segregation since they freeze to an intimate mixture of crystals, leaving little opportunity for the components to separate. On melting both components liquefy simultaneously with unlikely separation.

Table 3. PCM Types Include Paraffin Waxes, Non-Paraffin Organics, Hydrated Salts, and Metallics

Property or Characteristic	**Paraffin Wax**	**Non-Paraffin Organics**	**Hydrated Salts**	**Metallics**
Heat of Fusion	High	High	High	Med.
Thermal Conductivity	Very Low	Low	High	Very High
Melt Temperature (°C)	-20 to 100+	5 to 120+	0 to 100+	150 to 800+
Latent Heat (kJ/kg)	200 to 280	90 to 250	60 to 300	25 to 100
Corrosive	Non-Corrosive	Mildly Corrosive	Corrosive	Varies
Economics	Medium	High to very high	Low cost	Medium to High
Thermal Cycling	Stable	Elevated Temperature Can Cause Decomposition	Unstable over Repeated Cycles	Stable
Weight	Medium	Medium	Light	Heavy

IV. Thermal Energy Storage Via Chemical Reactions

Normally, a chemical energy storage system is comprised of one or more chemical compounds. The chemical TES category includes sorption and thermo chemical reactions. In thermochemical energy system, energy is stored after a dissociation reaction and then recovered in a chemically reverse reaction [12]. During this completely reversible chemical reaction, the temperature of some substances could probably be increased or decreased. Hence, this chemical heat energy can be stored through some effective methods for a long-term storage application. The heat stored depends on the amount of storage material, the endothermic heat of reaction and the extent of conversion [13].

High energy density (i.e.300 kWh/m3) TES systems can be achieved using chemical reactions (e.g. thermo-chemical storage, TCS) [8]. Thermo-chemical reactions, such as adsorption (i.e. adhesion of a substance to the surface of another solid or liquid), can be used to store heat and cold, as well as to control humidity. Typical applications involve adsorption of water vapour to silica-gel or zeolites (i.e. micro-porous crystalline alumino-silicates). Of special importance for use in hot/humid climates or confined spaces with high humidity are open *sorption* systems based on lithium-chloride to cool water and on zeolites to control humidity. Figure 2 shows an example of thermal energy storage by an adsorption process (e.g. water vapour on zeolite): during charging, water molecules are desorbed from the inner surface of the adsorbent. The TES remains in this state until water molecules can be adsorbed by the adsorbent and the TES is discharged again.

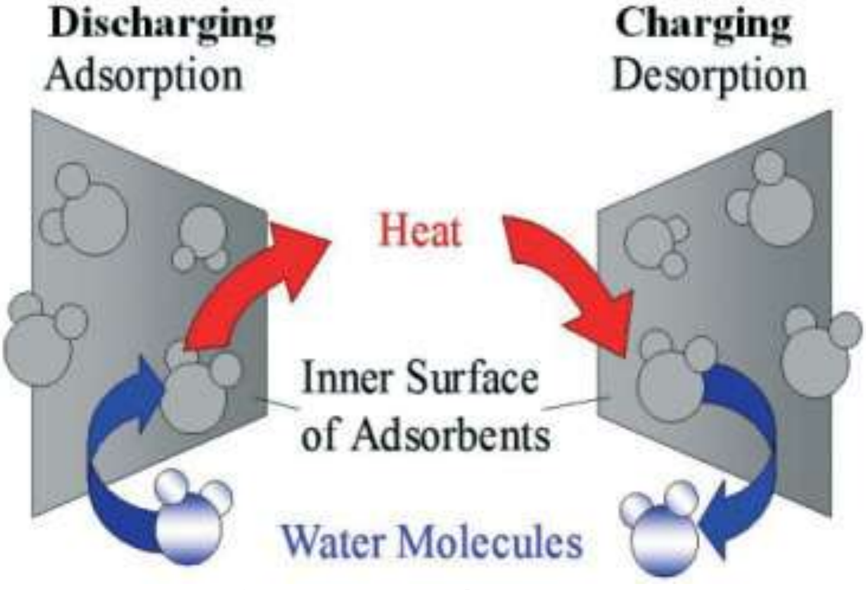

Figure 2 – TES De/Adsorption Process

Thermo chemical materials TCMs are a promising new alternative for long-term heat storage. The process concerned is based on a reversible chemical reaction, which is energy demanding in one direction and energy yielding in the reverse direction. Normally, TCMs have the higher storage density with repetitive storage properties to use in sorption storage systems, and some of the materials may even offer storage density close to the properties of biomass [14]. Because of higher energy density, thermo chemical TES systems can provide more compact ES relative to latent and sensible TES [15, 16]. Numerous research work and experiments on various storage methods have shown that thermo chemical ES systems have the potential to become probably the most effective and economic method of storing and utilizing waste heat [17, 18]
(Table 4).

Table 4 Shows some of the sorption materials that are currently under investigation

Material	Density(ρ), kg/m3	Energy density, MJ/m3
Aluminium oxide, Al_2O_3	3970	4320
Barium oxide, BaO	5720	4906
Borax, $Na_2B_4O_2.10H_2O$	1730	1218
Calcium oxide, CaO	3300	6158
Magnesium oxide, MgO	3580	6874

4.1 CHP storage systems

CHPs are a representative of chemical thermal energy conversion and storage systems [19]. Basically, a CHP makes use of transformation between thermal power and potential energy [20]. Specifically, CHPs utilize the reversible chemical reaction and sorption to change the temperature level of the thermal energy stored by chemical substances [21, 22]. These chemical materials play a significant role in absorbing and releasing heat [23]. According to the characteristic of the chemical reaction, various chemical materials could be involved in CHPs. A CHP system can be sorted as a mono-variant system and a di-variant system [20, 22].

V. Economic Analysis Of Thermal Energy Systems

Cost estimates of TES systems include storage materials, technical equipment for charging and discharging, and operation costs. TES systems for sensible heat are rather inexpensive as they consist basically of a simple tank for the storage medium and the equipment to charge/discharge. Storage media (e.g. water, soil, rocks, concrete or molten salts) are usually relatively cheap. However, the container of the storage material requires effective thermal insulation, which may be an important element of the TES cost. A number of seasonal TES have been installed in Germany [24]. Most systems consist of a 5,000-10,000 m3 water container with energy content between 70-90 kWh/m3 and investment costs between €50-200/m3 of water equivalent, thus translating into a specific investment cost from €0.5-3.0 per kWh.In the case of UTES systems, boreholes and heat exchangers to activate the underground storage are the most important cost elements. Specific costs range from €0.1-10 per kWh and depend heavily on local conditions.

Phase change material (PCM) storage and thermo-chemical storage (TCS) systems are significantly more complex and expensive than the storage systems for sensible heat. In most cases (e.g. thermo-chemical reactors), they use enhanced heat and mass transfer technologies to achieve the required performance in terms of storage capacity and power, and the cost of the equipment is much higher than the cost for the storage material. In general, the cost of a PCM system ranges between €10-50 per kWh [24]. The cost of systems using expensive micro-encapsulated PCMs, which avoid the use of heat exchange surfaces, can be even higher. For example, the cost of complete plaster board (€17/kg) with micro-encapsulated paraffin to be used as a passive cooling device within building structures (e.g. gypsum boards) includes the price of paraffin (about €5/kg) and the micro-encapsulated material (€13/kg)

The difference between the pure PCM and the complete TES system is even higher for active PCM installations. As an example, the costs of a calcium-chloride storage for the heat rejected from a thermally-driven absorption chiller includes the cost of calcium-chloride, which is rather inexpensive (€0.3/kg) and the cost of a container, heat exchanger and other components that is around €65/kWh. Materials for thermo-chemical storage (TCS) are also expensive as they have to be prepared (e.g. pelletised or layered over supporting structures). Also expensive are the containers and the auxiliary TCS equipment for both heat and mass transfer during energy charging and discharging. TCS systems can be operated as either open systems (i.e. basically packed beds of pellets at ambient pressure) or closed systems. Open systems are often the cheapest option while closed systems need sophisticated heat exchangers. The TCS cost ranges from €8-100 per kWh .

VI. TES – Issues And Challenges

TES technologies face some barriers to market entry and cost is a key issue. Other barriers relate to material properties and stability, in particular for TCS. Each storage application needs a specific TES design to fit specific boundary conditions and requirements. R&D activities focus on all TES technologies. Most of such

R&D efforts deal with materials (i.e. storage media for different temperature ranges), containers and thermal insulation development. More complex systems (i.e. PCM, TCS) require R&D efforts to improve reacting materials, as well as a better understanding of system integration and process parameters market development and penetration varies considerably, depending on the application fields and regions. Penetration in the building sector is comparably slow in Europe where the construction of new buildings is around 1.3% per year and the renovation rate is around 1.5%; of course, the integration of TES systems is easier during construction. The estimate of the European potential is based on a 5% implementation rate of TES systems in buildings. Penetration could be much higher in emerging economies with their high rates of new building construction. TES potential for co-generation and district heating in Europe is also associated with the building stock. The implementation rate of co-generation is 10.2% [17], while the implementation of TES in these systems is assumed to be 15%. As far as TES for power applications is concerned, a driving sector is the concentrating solar power where almost all new power plants in operation or under construction are equipped with TES systems, mostly based on molten salt. This is perhaps the most important development filed for large, centralised TES installations .In the industrial sector, about 5% of the final energy consumption is assumed to be used by TES installations. In particular, the use of industrial waste heat is expected to grow since the price of fossil fuels will rise and energy efficiency will be the key to competitiveness. Based on the University of Lleida study, the expansion of TES technologies is expected to be significant in Europe and Asia (particularly Japan) and somewhat lower (50%) in the United States. The global potential is estimated at approximately three times the European potential.

VII. Conclusion And Outlook

Higher inlet temperatures and higher flow rates of heat transfer fluid systems are required for the smooth functioning of TES. The retrieval time and amount of energy stored are high for a combination of Sensible Heat Storage (SHS) and Latent Heat Storage (LHS) system. Hence the usage of a combined SHS and LHS system is recommended. In the case of charging and discharging processes, little differences exist between the use of paraffin and stearic acid as PCMs. However latent heat and thermal conductivity variation proves that paraffin's performance is slightly better (5-7%). But both PCMs are suitable for TES systems

The significant advantages of Thermal Energy Storage (TES) systems include little energy loss during the storing operation, higher energy densities and the possibility of attaining more compact systems. In order to enhance the knowledge of the engineering and scientific characteristics of thermochemical TES systems further research is necessary. The performance and implementation of these systems can be analysed and improved only by conducting such studies. Thermochemical material forms a significant component of such systems. The selection of thermochemical materials are affected by their availability, cost, durability, energy density, degradation and cyclic behaviour. Further studies are required on the topics of design factors, safety, size, efficiency, maintenance, economics and installation. Along with this broad analyses of these systems should be carried out with the main focus on energy and exergy required. Such analyses can help in optimization and improvement of design. Many works are going on in this field and can be hoped that it will be fruitful in terms of new findings and experimental results.

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