TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics and Mechanics
Vol. 55, Issue IV, 2012

SEASONAL THERMAL ENERGY STORAGE CONCEPTS

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Abstract: *The energy storage systems can contribute significantly to meeting society`s need for more efficient, greening use in building heating and cooling, and domestic hot water applications. Another significant advantage of efficient energy storage is that, although it may have been designed primarily for the storage of solar energy, it is not restricted to that. This literature review paper attempts to summarize developments of seasonal solar thermal energy storage, using different storage concepts. The aim is to provide the basis for development of new intelligent seasonal thermal energy storage possibilities for use in combination with space heating and domestic hot water applications.* ***Key words:*** *thermal energy storage, heat storage, storage of thermal energy, seasonal heat storage, technologies for seasonal heat storage, sensible energy storage, latent energy storage, thermo chemical energy storage.*

1. INTRODUCTION

Thermal energy storage is required when heat demand does not match heat production. The interest in large-scale seasonal solar thermal energy storage started with the oil crisis in the early seventies. The objectives of seasonal thermal energy storage systems are designed to collect solar energy during the summer and retain the stored heat for use during the winter. These systems contribute significantly to improving the energy efficiency and reducing the greenhouse gas emissions to the atmosphere. One main factor that limits its application is that it is a cyclic, time-dependent energy source.

Energy demands in buildings vary on daily, weekly and seasonal basis. These demands can be matched with the help of thermal energy storage systems that operate synergistically and are carefully matched to each specific application. Thermal energy storage systems have the potential of making the use of thermal equipment more effective, and are important means of offsetting the mismatch between thermal energy availability and demand. Well designed systems can reduce initial and maintenance costs and improve energy efficiency [8].

A variety of thermal energy storage systems techniques for heating and cooling applications have been developed over the past decades. Increasing energy demands, shortages of fossil fuels and environmental concerns are increasing the interest in the development of economically competitive and reliable means of seasonal storage of thermal energy. Different examples about the efficient utilization of natural and renewable energy sources, cost savings and increased efficiency achievable through the use of seasonal thermal energy storage systems can be considered [6],[8].

The main issue impeding solar thermal technologies from achieving their full potential for space heating (or cooling) and domestic hot water applications is related to the fact that the energy source has intermittent nature and its effective utilization is dependent on the availability of efficient and effective energy storage systems [8].

2. CLASSIFICATION OF SOLUTIONS STORAGE TECHNOLOGIES

Classification of solutions storage technologies can be done taking into account several criteria. In figure 1 is presented a classification of solutions storage technologies based on the criterion of the state of the energy storage material.

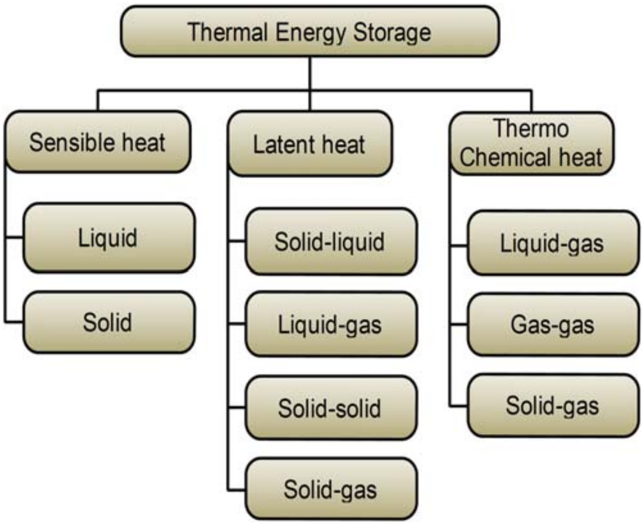

Fig. 1. Classification of thermal energy storage technology based on the criterion of the state of the energy storage material

The main technological concepts for thermal energy storage (heat/cold) are presented in figure 2.

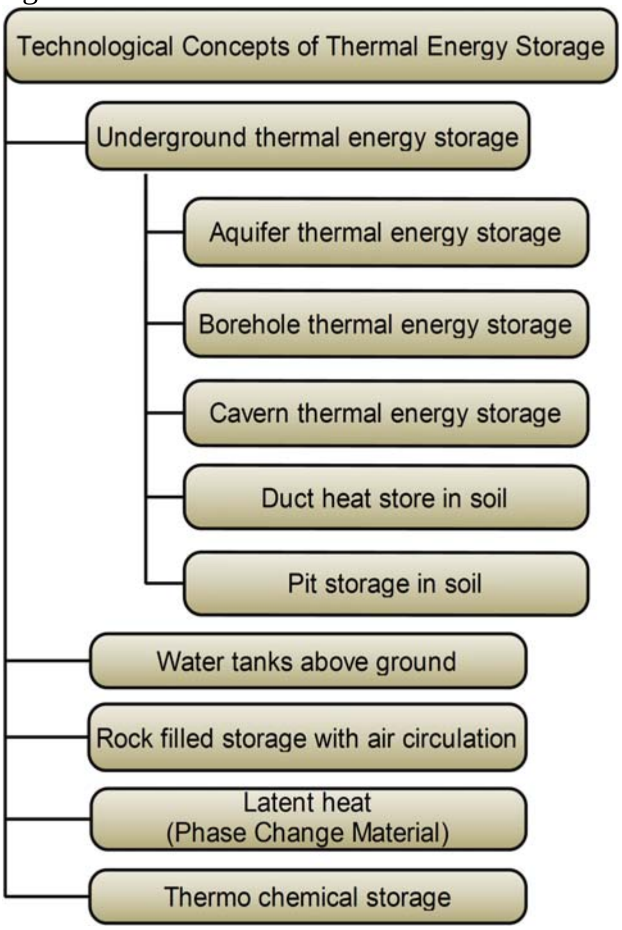

Fig. 2. Technological concepts of thermal energy storage

Most heat storage concepts with the exception of phase change material and thermo chemical storage have one basic challenge in common. When heat or cold is charged into or discharged from the store, there will be temperature differences in different parts of the storage volume. It is then of the utmost importance that the storage medium can maintain a structured layer, for instance with the warmest water on the top, and the coldest at the bottom. The effective storage capacity will be drastically reduced if mixing occurs and the overall temperature approaches some sort of average value over the whole volume [7].

In figure 3 is presented different types of liquid form for heat storage. The most commonly used liquid for sensible heat storage is water. Nowadays, with the reasonable cost and simple implementation, water storage technology is widely used in the solar thermal engineering field, according to the aforementioned characteristics:

- Water has relatively high specific heat capacity and almost no degradation under thermal cycling.
- Water has good compatibility with most of containment material (stable, mild and no corrosive chemical properties).
- Water is widely available and cheap.

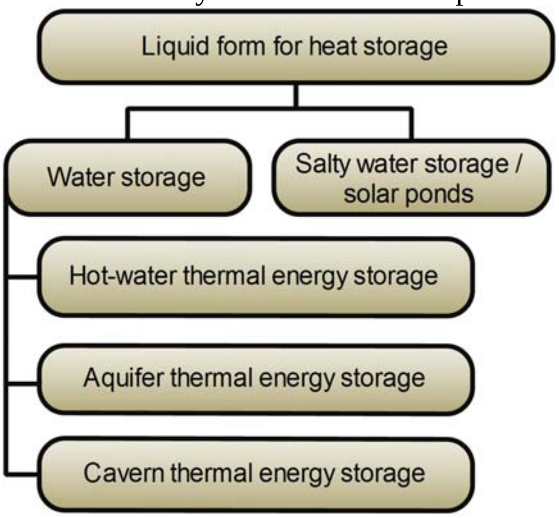

Fig. 3. Different types of liquid form for heat storage

Due to the relatively developed theoretical and practical technology, the sensible water thermal storage technology has not only been used for short term (diurnal) thermal storage, but also for long term (seasonal) thermal storage. Seasonal thermal storage has longer thermal storage period, generally three or more months. Thus, the seasonal energy storage can fully utilize the temperature differences between summer and winter, meeting or supplementing the heating/cooling demands for both seasons. Different from short term thermal storage technology, the seasonal thermal storage keeps the storage material at a lower temperature than that of short term storage, in order to reduce the thermal losses during the long storage period [12].

The advantages of water storage technology can be summarized as follows:

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

The disadvantages of water storage technology can be summarized as follows:

- Water might freeze or boil.
- Water is highly corrosive.
- Working temperatures are limited to less than 100°C and often have to be far below this boiling temperature.
- 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.

The difficulties and limitations relative to liquids can be avoided by using solid materials for storing thermal energy as sensible heat. In figure 4 it is presented a classification of different types of solid form for heat storage.

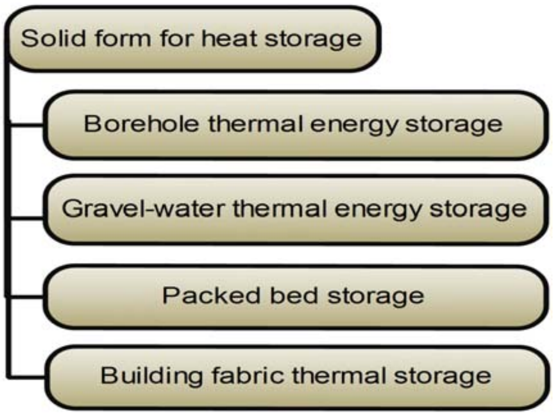

Fig. 4. Different types of solid form for heat storage

Direct contact between the solid storage media and a heat transfer fluid is necessary to minimize the cost of heat exchange in a solid storage medium. The use of rocks for thermal storage provides the following advantages:

- Rocks are not toxic and non-flammable.
- Rocks are inexpensive.
- Rocks act both as heat transfer surface and storage medium.
- The heat transfer between air and a rock bed is good, due to the very large heat transfer area, and the effective heat conductance of the rock pile is low, due to the small area of contact between the rocks. Then the heat losses from the pile are low [2].

3. SENSIBLE HEAT STORAGE SOLUTION

Generally speaking, there are five types of sensible seasonal thermal storage: hot water thermal energy storage, aquifer thermal energy storage, gravel-water thermal energy storage, borehole thermal energy storage, and cavern thermal energy storage.

Among these five storage methods, hot water thermal energy storage, aquifer thermal energy storage, and cavern thermal energy storage, belong to the type of sensible water thermal storage; borehole thermal energy storage belongs to the type of sensible solid storage; while gravel-water thermal energy storage is a combination of sensible liquids and sensible solids storage (figure 5).

The cost of the sensible heat storage solution mainly depends on the characteristics of the storage material. It is very common to utilize very cheap materials; for liquid such as water, oils and certain inorganic molten salts and solid like rocks, sands, pebbles and refractory as the storage medium. In the case of solids, the material is invariably in porous form and heat is stored or extracted by the flow of a gas or a liquid through the pores or voids.

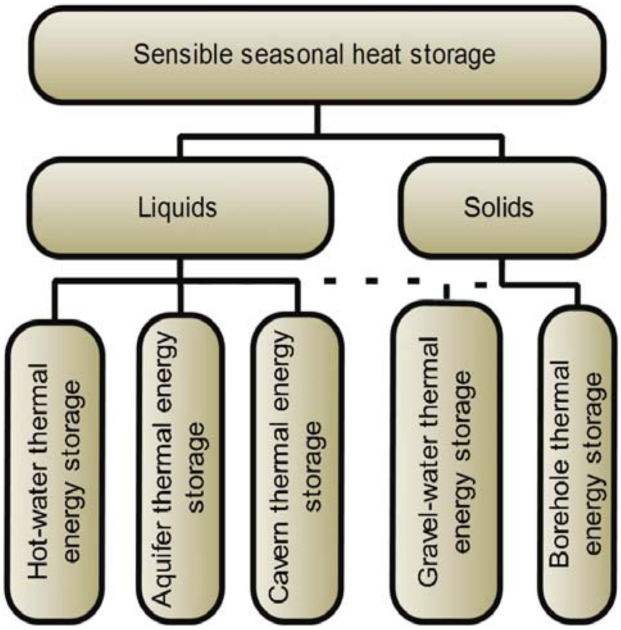

Fig. 5. Different types of sensible seasonal heat storage

Sensible heat storage systems are simpler in design than latent heat or thermo chemical storage systems. However they suffer from the disadvantage of being bigger in size and cannot store or deliver energy at a constant temperature [2].

3.1. Hot-water thermal energy storage

The hot-water thermal energy storage has the widest range of utilization possibilities. Because of the high specific heat capacity and the high capacity rates for charging and discharging it is the most favorable of the four storage types from the thermodynamic point of view.

The water filled tank (figure 6) construction of usually reinforced concrete is partly embedded into the ground and can be built almost independently from geological conditions. It is heat insulated at least in the roof area and on the vertical walls. It is usually built as steel or reinforced pre-stressed concrete tank, fully or partially buried in the ground [9],[10],[11].

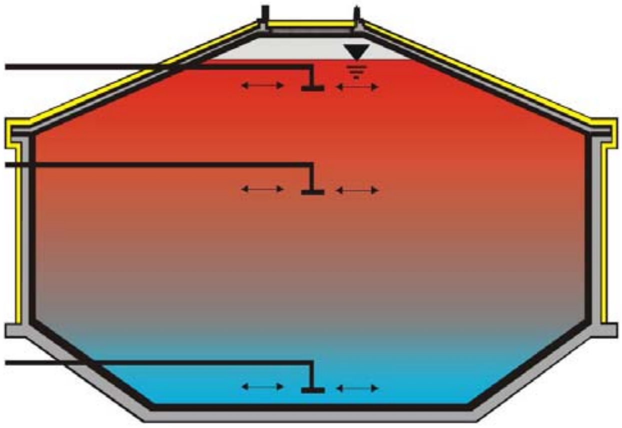

Fig. 6. Hot-water thermal energy storage

3.2. Aquifer thermal energy storage

Aquifers can be distinguished in water saturated porous aquifers in sand, gravel or eskers and fractured aquifers in limestone, sandstone, igneous or metamorphic rock [11]. Aquifers which are filled with groundwater have high hydraulic conductivity.

If there are impervious layers above and below and no or only low natural groundwater flow, they can be used for heat (and cold) storage. In this case, two wells or groups of wells are drilled into the aquifer and serve for extraction or injection of groundwater (figure 7) [10].

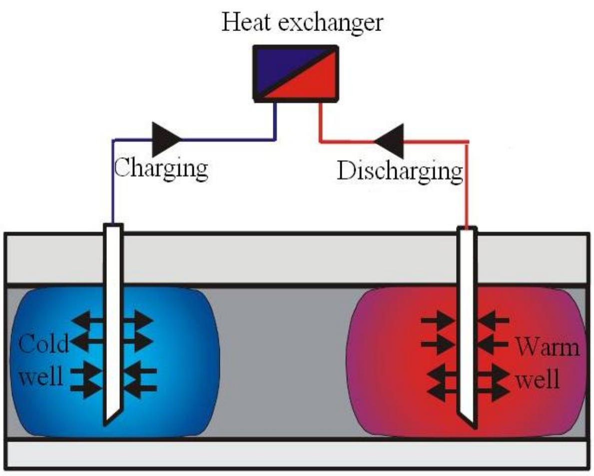

Fig. 7. Aquifer thermal energy storage

During charging periods cold groundwater is extracted from the cold well, heated up by the heat exchanger and injected into the hot well. In discharging periods the flow direction is reversed. Because of the different flow directions both wells have to be equipped with pumps, production- and injection-pipes [11].

For high temperature heat storage a good knowledge of the mineralogy, geochemistry and microbiology in the underground is necessary to prevent damage to the system caused by well-clogging, scaling etc [10].

3.3. Cavern thermal energy storage

One other form of storage is to use natural or artificial caverns where hot water can be stored. Such systems are not common due to the unavailability of suitable caverns.

The important parameters are for the rock to have low thermal conductivity, high stability and to be not leachable. Examples are metamorphic rocks like gneiss, igneous rocks and some hard sedimentary rocks [4].

Potential structures for cavern thermal energy storage are tunnels, abandoned mines, or rock caverns, natural karsts structures and artificially constructed caverns in rock or deep pits in soil.

When warm/hot water is first filled into the cavern, the heat losses to the surrounding rock mass will be substantial. However, during the first year or two after commissioning, the cavern will have developed a stable thermal halo around itself with decreasing temperature away from the warm/hot centre. There will still be a loss of heat, but dry rock is a poor heat conductor. The heat loss should be less than 10% during one operational cycle under favorable conditions. A crucial factor is ground water transport through the rock masses in the area, the less the better [7].

3.4. Gravel-water thermal energy storage

Gravel-water thermal energy storage (figure 8) are normally buried in the ground and need to be waterproofed and insulated at least at the side walls and on the top [8]. To avoid an expensive tank construction, gravel-water heat stores only have a plastic liner separating the storage material and the surrounding soil [11].

Charging and discharging can either take place by direct water exchange or via plastic pipes. Stratification should be supported by the charging devices. No load-bearing frame structure is required because forces are taken down to the side walls and to the bottom by the gravel. The store has heat insulation, at least at the side walls and on the top. Depending on the size and shape bottom insulation can be advisable as well. Because of the liner materials, operating temperatures are limited to approximately 90 °C.

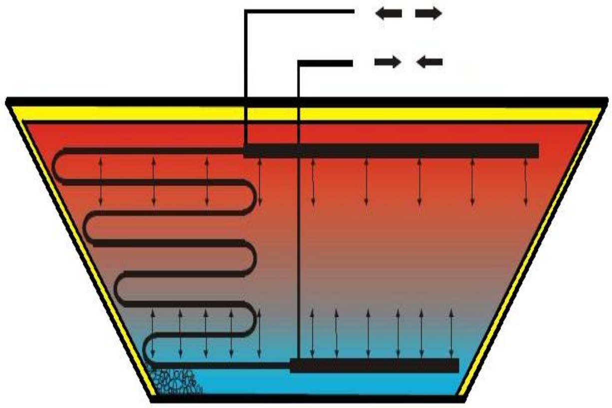

Fig. 8. Gravel-water thermal energy storage

The storage material usually is a mixture of gravel and water, also sand/water or soil/water mixtures are possible. Because of the reduced specific heat capacity, the volume of the store has to be approximately 50% bigger compared to a hot-water heat store to store the same amount of heat at the same temperature levels [10],[11].

3.5. Borehole thermal energy storage

In borehole thermal energy storage, heat is stored directly into the ground; it is transferred to the underground by means of conductive flow from a number of closely spaced boreholes.

The boreholes can be equipped with different kinds of borehole heat exchangers, making the boreholes act as a large heat exchanger between the system and the ground. The most common borehole heat exchangers are a single U-tube made of plastic pipes.

Heat or cold is delivered or extracted from the underground by circulating a fluid in a closed loop through the boreholes. The fluid consists of water, which is mixed with glycol or alcohol to allow the system to work below the freezing point, if so required [3].

Borehole thermal energy storage does not have an exactly separated storage volume. Heat is charged or discharged by vertical borehole heat exchangers which are installed into a depth of 30–200 m below ground surface (figure 9). At the top of the store there is a heat insulation layer to reduce heat losses to the surface.

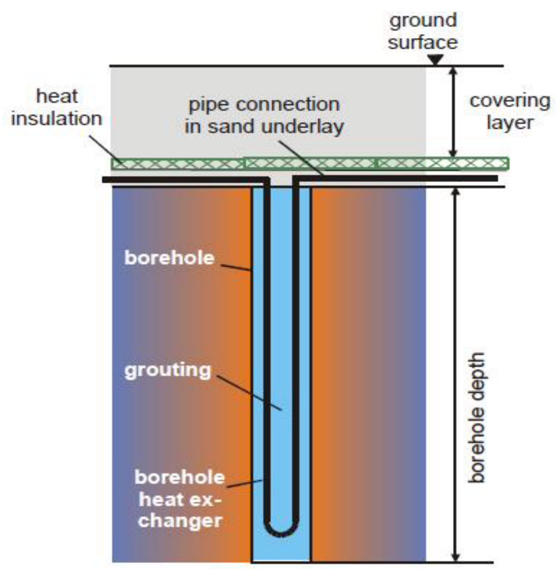

Fig. 9. Borehole heat exchangers

A certain number of heat exchangers are hydraulically connected in series to a row and certain rows are connected in parallel, or in a combination serial/parallel depending on the planned thermal loading and unloading of the facility. At charging, the flow direction is from the centre to the boundaries of the store to obtain high temperatures in the centre and lower ones at the boundaries of the store. At discharging the flow direction is reversed.

The most important parameters influencing the borehole thermal resistance are the thermal conductivity of filling material, the number of pipes, pipe position and the pipe thermal conductivity [9]. The shape of the storage facility, seen at the surface, can be adapted to the shape of the available land area as illustrated in figure 10 [7].

Borehole thermal energy storage does not have vertical temperature stratification as the stores discussed above but a horizontal stratification from the centre to the borders. That is because the heat transfer is mainly driven by heat conduction and not by convection. At the borders the temperature decreases because of the heat losses to the surroundings. The horizontal stratification is supported by connecting the supply pipes in the centre of the store and the return pipes at the borders [11].

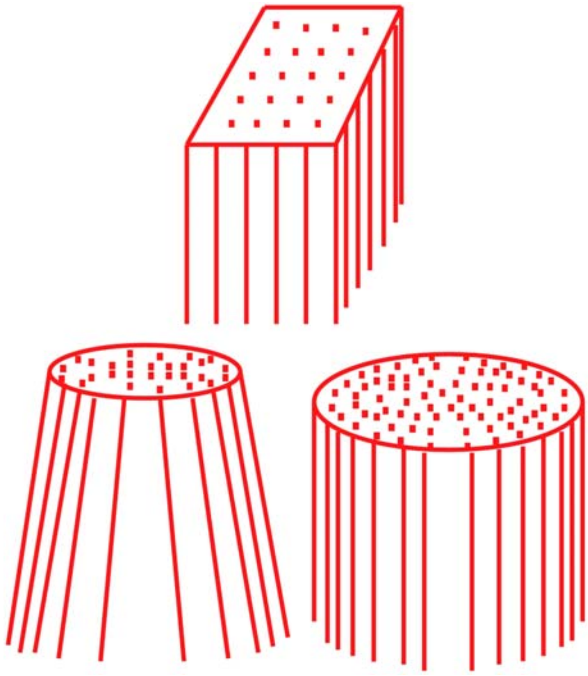

Fig. 10. Different drilling patterns that may be used in a borehole thermal energy storage facility

One advantage of this type is the possibility for a modular design. Additional boreholes can be connected easily and the store can grow with e.g. the size of a housing district. The size of the store has however to be between three to five times higher than that of a hot water heat store to obtain the same heat capacity. Because of the lower capacity at charging and discharging usually a buffer store is integrated into the system [10].

An important issue in the design of underground seasonal storage systems using borehole heat exchangers is to find cost-effective methods to construct the borehole thermal energy storage field so that heat can be injected or extracted from the ground without excessive temperature differences between the heat carrier fluid and the surrounding ground. As a result of the limited thermal conductivity the heat losses are rather moderate and storage efficiencies of 70% can be reached. In contrast good thermal contact between the heat exchangers and the ground is required to allow a good heat transfer rate per unit area of the heat exchanger tube [9].

Some important parameters for a successful borehole thermal energy storage project are: rock with high specific heat, medium to high thermal conductivity, and compact rock mass with (virtually) no ground water flow. Other important parameters are the type of rock including grain size and the types of minerals [7]. Suitable geological formations for this kind of heat storage are e.g. rock or water-saturated soils.

4. LATENT HEAT STORAGE SOLUTION

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 [2].

Phase change materials can therefore be used as a thermal storage medium for both heating and cooling. One common application is buffering of indoor temperature variations, and this means that heat and cold is stored in a temperature interval of only a few degrees. The use of phase change material for temperature buffering will lead to energy savings, and it is also expected that the thermal comfort will improve [7].

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 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.

Any latent heat thermal energy storage system should have at least the following three components: a suitable phase change material in the desired temperature range, containment for the storage substance, and a suitable heat carrying fluid for transferring the heat effectively from the heat source to the heat storage. Furthermore, the phase change materials undergo solidification and therefore cannot generally be used as heat transfer media in a solar collector or the load [2].

Phase change materials are either packaged in specialized containers such as tubes, shallow panels, etc., or contained in conventional building elements (wall board, ceiling) or encapsulated as self-contained grains [5].

In figure 11 are illustrated some application areas for phase change material in buildings. This are:

- No.1:Latent heat store for space heating.
- No.2:Plaster and compound systems with high heat storage capacity.
- No.3:Transparent insulation and day lighting schemes.
- No.4:Shading phase change material compounding system.
- No.5:Phase change material in gypsum products and paints.
- No.6:Phase change material to buffer temperature variations in solar-air-systems.

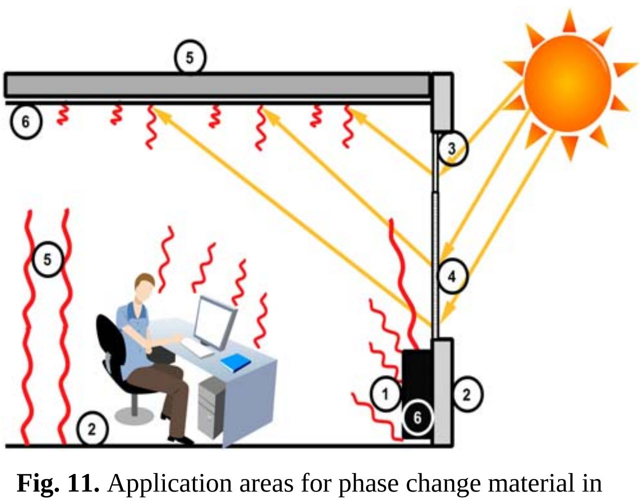

Fig. 11. Application areas for phase change material in buildings

Many phase change materials 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:

- 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 and weight must be kept to a minimum.
- The load is such that energy is required at a constant temperature or within a small range of temperatures.
- 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 [2].

5. THERMOCHEMICAL HEAT STORAGE SOLUTION

Energy may be stored in systems composed of one or more chemical compounds that absorb or release energy through bond reactions. There are many forms in which energy can be stored through bond reactions. Bond storage involves an endothermic reversible reaction, which can be reversed when required to release heat. The chemical produced can often be stored cold (without losses) and can often be transported easily [2].

Several reversible chemical processes, all of them involving two media, are being investigated for their suitability as a means of thermal storage.

One concept is using a salt, such as sodium sulphide and water. The salt can be dried using for instance solar heat. This will accumulate thermal energy, and this energy can be recovered by adding water vapor to the salt. Energy at a low temperature level has to be provided in order to discharge the storage, for instance vaporization of water. At the charging process is energy withdrawn from the system for instance by condensing water.

Another reaction is adsorption of water vapor in a zeolite material. Zeolites are alumina silicates with high micro-porosity and open structure. When dry zeolite material comes in contact with water vapor, the water vapor will enter the internal crystal lattice and causes a reaction that leads to the release of heat. The process is reversed by heating the zeolite material to more than 100 ^{0}C when the water is driven off (desorption). The adsorption and desorption processes can be repeated almost indefinitely without any significant deterioration of the zeolite material [7].

For a bond reaction to be considered for energy storage, the following conditions should be met:

- The reaction should be run near equilibrium, i.e. reversible.
- The reactant, with or without addition of a photo-sensitizer, should be able to use as much of the solar spectrum in the terrestrial atmosphere as possible.
- The energy stored in the bond energy should be large enough.
- The reactants should be cheap [2].

An important factor to be considered in bond process is the recovery of the reagents or the intermediary chemicals. It is estimated that in each chemical cycle, recovery yields of 99.9 or even 99.99 % have to be achieved if the bond process are to be viable [2].

Thermo chemical heat storage is more complex than other thermal energy storage systems, but they are also more flexible.

6. SUMMARY OF THERMAL ENERGY STORAGE

So far, the development of seasonal storage has been aimed at heating large district system stores instead of single house solutions, in order to fulfill technical viability and cost effectiveness by using large storage volumes. Compared to small solar domestic hot water systems for single-family houses, the solar heat cost can be cut at least in third. Long-term storage systems prove being more effective in reducing fossil fuels use and complying with CO_2 emission policies. Which of the technologies described above is selected depends very much on the local hydro-geological site conditions. Hot water storage tank are technically feasible and work well. However, construction costs and thermal losses are still too high. The main cost for hot-water storage tanks is caused by the concrete construction, ground works, insulation, and the use of steel liners to reduce water permeability. Considerable cost reductions can be obtained with the development of high-density concrete materials. For gravel-water stores, insulation and ground works account for significant part of the costs. Moisture protection of the insulation is important for both concepts. Natural aquifers are a cost effective seasonal storage concept but require water saturated sand layers with high permeability without ground water movement. Well construction is the predominant part of the costs for aquifer heat stores. The installation work for borehole heat exchangers, including material and drilling works, causes nearly half of the costs for borehole heat stores [9],[10],[11].

For all thermal energy storage concepts, a geological investigation has to be made in the pre-design phase. The decision to use a certain type mainly depends on the local conditions and, primarily, on the geological and hydro-geological situation in the ground below the respective construction site. The highest demands with regard to this are made by borehole and aquifer heat stores. The legal requirements have to be checked in the pre-design phase as well.

In most countries the usage of the ground for heat storage has to be approved by the local water authorities to make sure that no interests regarding drinking water are affected. This can also become necessary if the ground surrounding a storage tank is heated up by heat losses.

For the choice of a suitable storage concept for a specific plant all relevant boundary conditions have to be taken into account: local geological situation, system integration, required size of the store, temperature levels, power rates, legal restrictions etc. Finally, decisions should be based on an economic optimization of the different possibilities. After construction the stores have start-up times between three and five years, depending on the storage concept, to reach normal operating conditions. Within this time, the surrounding ground is heated up and the heat losses of the store are higher than during long-term operation [11].

A summary of the main parameters of the different concepts for seasonal sensible heat storage is shown in table 1.

Table 1

Comparison of storage concepts

Storage concept	**Hot-water**	**Gravel-water**
Storage medium	Water	Gravel-water
Heat capacity [kWh/m^3]	60-80	30-50
Storage volume for 1 m^3 water equivalent	1m^3	1.3-2m^3
Geological requirements	-stable ground conditions, -preferably no ground water, -5-15m deep.	-stable ground conditions, -preferably no ground water, -5-15m deep.
Storage concept	**Aquifer**	**Borehole**
Storage medium	Sand/Water-gravel	Soil/Rock
Heat capacity [kWh/m^3]	30-40	15-30
Storage volume for 1 m^3 water equivalent	2-3m^3	3-5m^3
Geological requirements	-natural aquifer layer, high hydraulic conductivity, -confining layers on top and below, -no or low natural ground water flow, -suitable water chemistry at high temperatures, -20-50m thickness.	-drillable ground, -ground water favorable, -high heat capacity, -high thermal conductivity, -low hydraulic conductivity, -natural ground water flow less than 1 m/a, -30-200m deep.

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Concepte de stocare a energiei termice sezoniere

Abstract: *Sistemele de stocarea energiei pot contribui în mod semnificativ la satisfacerea nevoilor societății cu privire la eficientizarea şi ecologizarea sistemelor de încălzire şi răcire ale locuințelor, precum şi în utilizarea apei calde menajere. Un alt avantaj semnificativ al eficienței stocării energiei, se referă la faptul că deşi au fost proiectate inițial pentru stocarea energiei solare, ele nu se rezumă numai la aceasta. Această lucrare încearcă să sintetizeze evoluția stocării energiei termice sezoniere utilizând diferite concepte de stocare a acesteia. Scopul este de a oferi o bază pentru dezvoltarea de noi posibilități inteligente de stocare a energiei termice sezoniere pentru a fi folosite în aplicații atât la încălzirea spațiilor de locuit cât şi la prepararea apei calde menajere.*

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