

# THERMAL ENERGY STORAGE

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## ABSTRACT

There are three main physical ways for thermal energy storage: sensible heat, phase change reactions and thermochemical reactions. Storage based on chemical reactions has much higher thermal capacity than sensible heat but are not yet widely commercially viable. Large volume sensible heat systems are promising technologies with low heat losses and attractive prices.

## 1. INTRODUCTION

Thermal energy is an important form of final energy e.g. in buildings and industry. Typically close to 1/3 of all final energy in northern climates go into heating of buildings. Basically all primary energy sources may be used to produce heat and in this way primary energy often have an inherent storage function.

The starting point of constructing energy systems is to strive for a balance of energy supply and demand, i.e. to minimize the need of storing final energy as this adds extra costs to the price of final energy. Examples when storage of thermal energy is needed include house heating systems, industrial processes or CHP power plants. The need of thermal energy storage may often be linked to the following cases:

- there is mismatch between thermal energy supply and energy demand;
- when of intermittent energy sources are utilized;
- compensation of the solar fluctuation in solar heating systems.

Possible technical solutions to overcome the thermal storage need may be the following:

- building production over-capacity;
- using a mix of different supply options;
- adding back-up/auxiliary energy systems;
- only summer-time utilization of solar energy;
- short/long-term thermal energy storage.

In traditional energy systems, the need for thermal storage is often short-term and therefore the technical solutions for thermal energy storage may be quite simple, or in most cases water storage.

Energy storage for intermittent thermal sources such as solar heating is important as the storage demand may be quite long. Especially, if the solar heating system is intended to provide a high solar fraction, i.e. most of the heat supplied over the whole year is solar heat, thermal storage becomes very important and challenging.

Figure 1 illustrates the variation of the solar radiation for a range of sites. It

shows that the differences in the maximum solar radiation for different latitudes are much smaller than for the minimum values. The storage need in a solar system is often determined by the ratio of the maximum to minimum monthly solar radiation. When the max-min ratio is less than 5, even wintertime solar may be enough to provide the heat load whereas values higher than 10 means such a large fluctuation that seasonal storage or back-up system is necessary. In high northern-Europe, the winter solar radiation falls under the utilization limit.

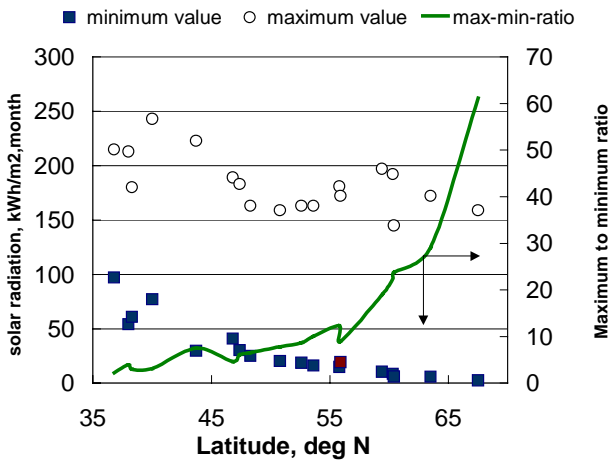


Figure 1. The solar fluctuation.

## 2. PHYSICS OF THERMAL STORAGE

When a thermal storage need occurs, there are three main physical principles to provide a thermal energy function:

### (1) SENSIBLE HEAT

The storage is based on the temperature change in the material and the unit storage capacity [J/g] is equal to heat capacitance  $\times$  temperature change.

### (2) PHASE-CHANGE

If the material changes its phase at a certain temperature while heating the

substance then heat is stored in the phase change. Reversing, heat is dissipated when at the phase change temperature when it is cooled back. The storage capacity of the phase change materials is equal to the phase change enthalpy at the phase change temperature + sensible heat stored over the whole temperature range of the storage.

### (3) CHEMICAL REACTIONS

The sorption or thermochemical reactions provide thermal storage capacity. The basic principle is as follows:  $AB + \text{heat} \leftrightarrow A + B$ ; using heat a compound AB is broken into components A and B which can be stored separately; bringing A and B together AB is formed and heat is released. The storage capacity is the heat of reaction or free energy of the reaction.

Figure 2 illustrates the change of storage capacity Q for the three different thermal storage types as a function of temperature or fraction of compound ( $X=B$ ).

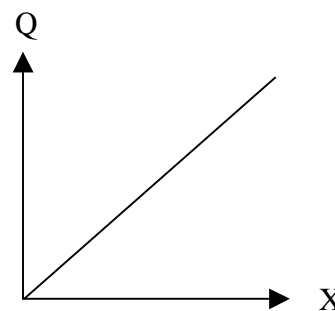
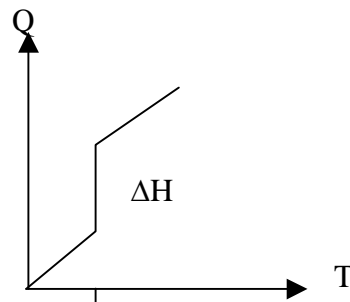
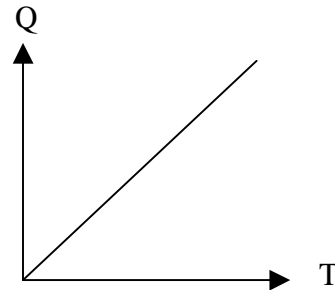


Figure 2. Storage capacity Q for different thermal storage systems.

The storage systems based on chemical reactions have negligible losses whereas a sensible heat storage dissipates the stored heat to the environment and need to be isolated.

### 3. STORAGE MATERIALS

Materials are the key issues for thermal storage. There are a large range of different materials that can be used for thermal storage as shown by Table 1. The most common storage medium is water. The classical example for phase change materials is the Glauber salt (sodium sulphate). Metal hydrides are well-known hydrogen stores in which hydrogen is absorbed into the metallic structure with the help of heat, or turning it around, adding hydrogen would release heat and removing hydrogen absorb heat. In this way metal hydrides also work as thermochemical heat storage ( $AB=MeH_x$ ).

Table 1. Examples of materials suitable for thermal storage

<b>SENSIBLE HEAT</b>	
<ul style="list-style-type: none"> <li>• water, ground, rock, ceramics</li> <li>• T=60-400 °C</li> </ul>	
<b>PHASE-CHANGE</b>	
<ul style="list-style-type: none"> <li>• inorganic salts, inorganic and organic compounds; classical examples :</li> <li>• <math>Na_2SO_4 \times 10 H_2O + heat (24 \text{ }^\circ C) \leftrightarrow Na_2SO_4 + 10H_2O</math></li> <li>• <math>CaCl_2 \times 6 H_2O (30 \text{ }^\circ C)</math></li> <li>• Paraffins (melting at 20-60 °C)</li> </ul>	
<b>CHEMICAL REACTIONS</b>	
<ul style="list-style-type: none"> <li>• <math>S \times n G + heat \leftrightarrow S \times m G + (n-m) \times G ; G (g) \leftrightarrow G(liq)</math></li> </ul>	
G=working fluid/gas	S=sorption material
water	hydroxides ,hydrates
ammonia	ammoniates
hydrogen	metal hydrides
carbon dioxide	carbonates
alcohols	alcoholates

One of the most interesting physical parameters of a thermal storage is its storage capacity and temperature range. These two parameters determine the size and suitability of the storage to an application, respectively. Table 2 gives a summary of the storage capacity and temperature range for some important potential storage materials.

Table 2. Storage capacity.

Medium	temperature [C-deg]	capacity [kWh/m3]
Water	DT=50 oC	60
Rock		40
Na2SO4x10H2O	24	70
CaCl2x6H2O	30	47
paraffine	20-60	56
lauric acid	46	50
stearic acid	58	45
pentaglycerine	81	59
butyl stearate	19	39
propyl palmitate	19	52
Silica gel N+H2O	60-80	250
Zeolite 13 X +H2O	100-180	180
Zeolite + methanol	100	300
CaCl2+ammonia	100	1000
MeHx+H2	50-400	200-1500
Na2S+H2O	50-100	500

The storage capacity of water in a typical house heating application is about 60 kWh/m<sup>3</sup>. For comparison, the storage capacity of oil is about 10 MWh/m<sup>3</sup>. Phase change materials (PCM) based on hydrates or fatty acids have a phase change heat of the same order as the whole storage capacity of water. If adding the sensible heat of the PCM then the storage capacity of the PCM would be doubled.

As the PCM has a sharp change in the storage capacity at a single temperature point (phase change temperature), it can be used for temperature regulation. For example, mixing PCM into the building material could increase the thermal capacity of a wall manifold. A wall has

typically an effective  $\Delta T$  of around 10-15 °C which gives a storage capacity of 10 kWh/m<sup>3</sup> which is about 1/5<sup>th</sup> of that of paraffine. Mixing two different PCMs in a suitable proportion gives the possibility to match the phase change temperature exactly with the temperature of the application.

Thermochemical storage materials have the highest storage capacity of all storage media. Some of the materials may even approach the storage density of biomass. Solid silica gel has a storage capacity which is up to about 4-times that of water.

Water storage is the main commercially available thermal storage systems. Small PCM storage units have been sold mainly for special applications. Both PCM and thermochemical storage needs still R&D efforts to be practical.

#### 4. LARGE SCALE STORAGE SYSTEMS

To compensate for the low storage capacity, large sensible heat systems have been planned for applications with large capacity needs, e.g. when having a long-term heat storage need.

One important advantage of a large size is that the relative heat losses decrease with increasing size. The relative heat losses are proportional to the perimeter area/volume, or,  $V^{2/3}/V = V^{-1/3}$ . Therefore as  $V \rightarrow \infty$ , the relative losses  $\rightarrow 0$ .

When going into large storage systems other technologies than water tank may be employed. If the storage requirement is less than a few thousand m<sup>3</sup>, or <100 MWh, then ordinary insulated steel tanks are the cheapest alternative. For larger volumes, different subsurface storage concepts become interesting due to much

lower costs. Thus the best sensible heat storage technology may change with the capacity needed. The following example demonstrates the reduction of unit costs of storage when increasing the size of the storage and choosing the optimal storage concept:

- 1 m<sup>3</sup> water storage 1,000 EUR/m<sup>3</sup>
- 10,000 m<sup>3</sup> earth pit 40 EUR/m<sup>3</sup>
- 100,000 m<sup>3</sup> rock cavern 10 EUR/m<sup>3</sup>

Figure 3 demonstrates the different large-scale sensible heat technologies available. Concepts like earth pits or rock caverns are large water reservoirs built into ground. Aquifer storage employs the storage capacity of water mixed ground. The aquifer storage is very simple and needs only a few wells to operate. Vertical pipes may be laid into ground enabling use of the thermal capacity of ground. Ground heat storage may also be employed effectively through heat pumps yielding a larger  $\Delta T$ .

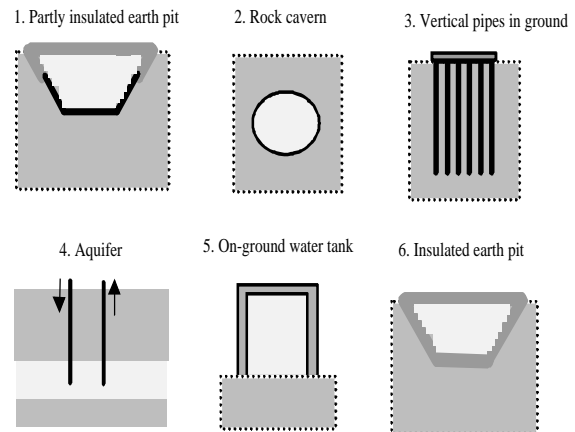


Figure 3. Seasonal storage options for large-scale applications.

#### 5. SEASONAL STORAGE SOLAR HEATING SYSTEMS

Long-term heat storage of solar energy from summer into winter is one of the key questions for large-scale utilization of solar energy, or, to reach a high fraction of non-purchased energy in an

individual application. There exist a few different approaches to the storage including large storage installations described above, small individual units, and finally system approaches e.g. improving collector U-value to enable heat production in winter to overcome the intermittence question.

Technical developments with central solar heating plants with seasonal storage (CSHPSS) applicable for a group of houses and super-insulated water tanks for one-house low energy loads, have brought seasonal storage applications closer to reality.

The CSHPSS systems are typically built for heat loads ranging in size from tens of houses up to hundreds of houses. The collector size of such systems may be in the range of 500-100,000 m<sup>2</sup> and the storage volume 1,000-500,000 m<sup>3</sup>. The largest CSHPSS built so far has a 4,320 m<sup>2</sup> collector field and 105,000 m<sup>3</sup> rock cavern storage. The smallest seasonal storage systems built are for single-family houses and the collector area would then be 40-70 m<sup>2</sup> and the storage volume 50-200 m<sup>3</sup> of water.

To increase the solar fraction in the traditional active solar heating system for a residential hot water, would in practice require larger storage capacities than usually used. If for instance all of the heating demand load of a well-insulated house would be supplied by a up-to-date active solar heating system, a 25 m<sup>2</sup> collector area and 85m<sup>3</sup> storage water tank with 100 cm insulation around would be. This example demonstrates well the present technological state for single houses: the solar collector technology is already sufficient, but the storage technology is still too primitive and needs major improvements. Improving the energy storage capacity of

the storage unit would also dramatically improve the practical possibilities for storage. The chemical storage concepts discussed earlier may thus be quite relevant in this context.

Through improved materials and collector technology, it may be perceived that collectors could be better optimised for low solar radiation conditions, i.e. especially for wintertime conditions. An analysis on the effect of the collector technology on the storage requirement is shown in Fig. 4 where the required collector area and storage volume to fully satisfy the remaining heat load of a low energy house (6 MWh/a) through active solar heating is given. With a 70% solar fraction, the storage volume would drop to about one half. It is clearly seen that the collector area needed to supply the solar heat is less affected when  $U < 2.0$  W/m<sup>2</sup>K, whereas the storage requirement decreases steadily with improved collectors.

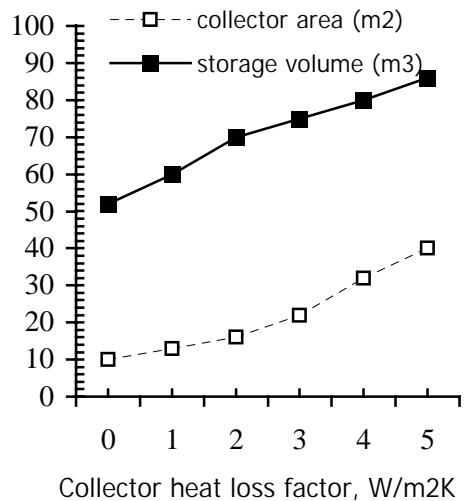


Figure 4. Thermal storage and collector requirement versus collector technology improvements to achieve a 100% solar fraction (central Europe).