

***Thermal Energy Storage***  
***A State-of-the-Art***

**A report within the research program**  
***Smart Energy-Efficient Buildings***  
**at NTNU and SINTEF**  
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## **1. Introduction**

This report is the first work done on subtask 3.4 "Thermal energy storage" as part of the multidisciplinary project "Smart Energy Efficient Buildings" (Smartbuild). The project is a joint endeavour with NTNU and SINTEF as participants, and will run for 4 years after its start-up in 2002.

The aim of Smartbuild is to develop new knowledge with integrated technological solutions that will enable us to cover our building related energy needs with substantially less harmful environmental impacts. At the same time shall we satisfy the whole range of end user needs such as comfort, aesthetics, costs, operability, reliability and functionality. In order to accomplish this task, we will need input from and co-operation between a wide range of experts in the field of energy use in buildings. These include architects, designers, engineers, social scientists, and the Norwegian building industry and its suppliers.

The scope of the present report on thermal energy storage is primarily to provide information for other project participants in order to facilitate discussion and co-operation between our different fields of expertise, and to encourage development of new and integrated technical solutions. The report is therefore not meant to be a state-of-the-art documentation for experts in the field of thermal energy storage.

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## 2. Central concepts

It is economically inefficient, in all production processes, to install production and distribution equipment with the capacity to accommodate for the maximum (short-term) demand. Furthermore, productivity decreases when production equipment cannot operate at full capacity in periods of reduced demand.

Consequently, manufacturing processes will seek to operate at optimum capacity, and store surplus production in periods with less market demand. This principle is, however, not feasible in most of today's conventional energy production and distribution systems.

The basic idea behind thermal storage in the building sector is to provide a buffer to balance fluctuations in supply and demand of low temperature thermal energy for space heating and cooling. The demand fluctuates in cycles of 24 hour periods (day and night), intermediate periods (e.g. seven days) and according to seasons (spring, summer, autumn, winter). Systems for storing thermal energy (heat/cold) should therefore reflect these cycles, with either short-term, medium term or long-term (seasonal) storage capacity.

The energy sources normally used for heating and cooling are oil, gas, coal and electricity. However, it is not entirely logical, nor efficient, to burn fossil fuels at temperatures up to 1000 degrees in order to create an indoor climate at 20-25 degrees. Further, burning of fossil fuels emits greenhouse gases. Neither is it efficient to use electric power, a form of highly processed energy, only for resistance heating (Narita, 1997).

There are basically three types of thermal storage devices being investigated at present by the international research society and some industrial players:

- Specific (sensible) heat storage
- Latent heat storage (phase change materials)
- Thermochemical heat storage

The principal gain from thermal storage is that heat and cold may be moved in space and time to allow utilisation of thermal energy that would otherwise be lost because it was available at the wrong place at the wrong time. Thermal energy storage systems themselves do not save energy. However, energy storage applications for energy conservation enable the introduction of more efficient, integrated energy systems.

Thermal energy storage therefore makes it possible to more effectively utilise new renewable energy sources (solar, geothermal, ambient) and waste heat/cold recovery for space heating and cooling.

Thermal energy storage can consequently serve at least five different purposes:

- Energy conservation utilising new renewable energy sources.
- Peak shaving both in electric grids and district heating systems.
- Power conservation by running energy conversion machines, for instance co-generating plants and heat pumps, on full (optimal) load instead of part load. This reduces power demand and increases efficiency.
- Reduced emissions of greenhouse gases.
- Freeing high quality electric energy for industrial value adding purposes.

### 3. Technology and markets

The main technological concepts for thermal energy storage (heat/cold) are:

- Underground thermal energy storage (UTES)
- Water tanks above ground
- Rock filled storage with air circulation
- Phase change materials (PCM)
- Thermochemical storage

Most heat storage concepts with the exception of PCM and 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. (See section 3.2).

#### 3.1 Underground thermal energy storage (UTES)

Underground thermal storage is mostly used for seasonal heat/cold storage. The main concepts illustrated in Figure 1 are:

- Aquifer thermal energy storage (ATES)
- Borehole thermal energy storage (BTES)
- Cavern thermal energy storage (CTES)
- Ducts in soil
- Pit storage

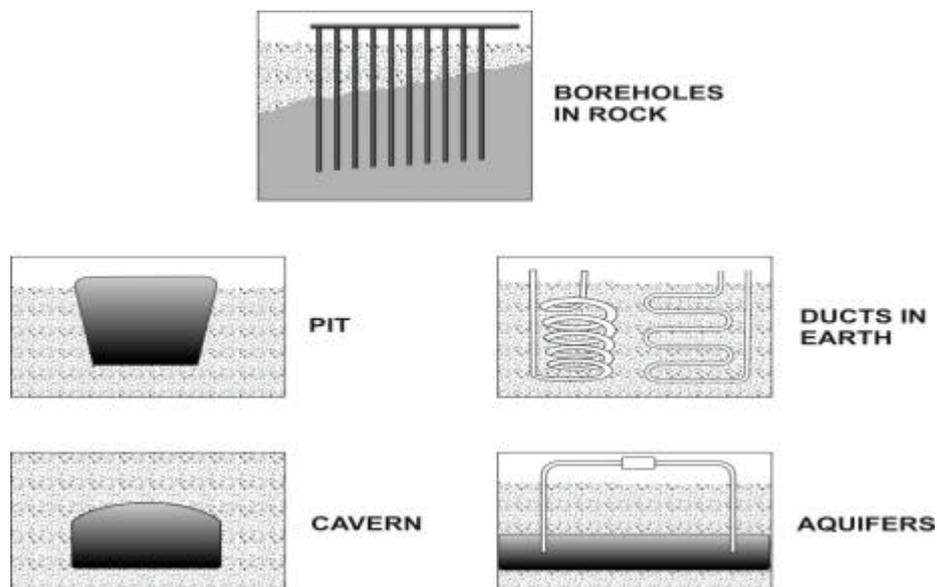


Figure 1. Main concepts for Underground Thermal Energy Storage (UTES).

There are no standard designs of UTES installations. Each facility will be unique to a large extent, even if the basic principles are similar. This means that each installation is more or less “tailor made”, even if components like pumps, pipes, heat exchangers etc. are standard industrial products. There is consequently not a market for UTES as an industrial product in the traditional sense.

### 3.1.1 Aquifer thermal energy storage

There are two basic principles for aquifer thermal storage: Cyclic regime and Continuous regime as illustrated in Figure 2. A plant can also be made with groups of wells instead of just two single wells.

With a cyclic regime, cold and heat can be stored below/above the natural ground temperature, whereas the continuous regime can only be used where the load can be met with temperatures close to natural (existing) ground temperatures. The storage part is therefore an enhanced recovery of natural ground temperatures. Some pros and cons of the two regimes are:

- Cyclic flow will create a definite cold and heat reservoir around each well or group of wells. It is possible to maintain a ground volume above or below the natural ground temperature all the time. One disadvantage is a more complicated well design and control system with each well being able to both produce and inject ground water.
- Continuous flow is simpler with regard to system design and well control, and only one well or group of well need to be equipped with pumps. The disadvantage is the limited temperature range.

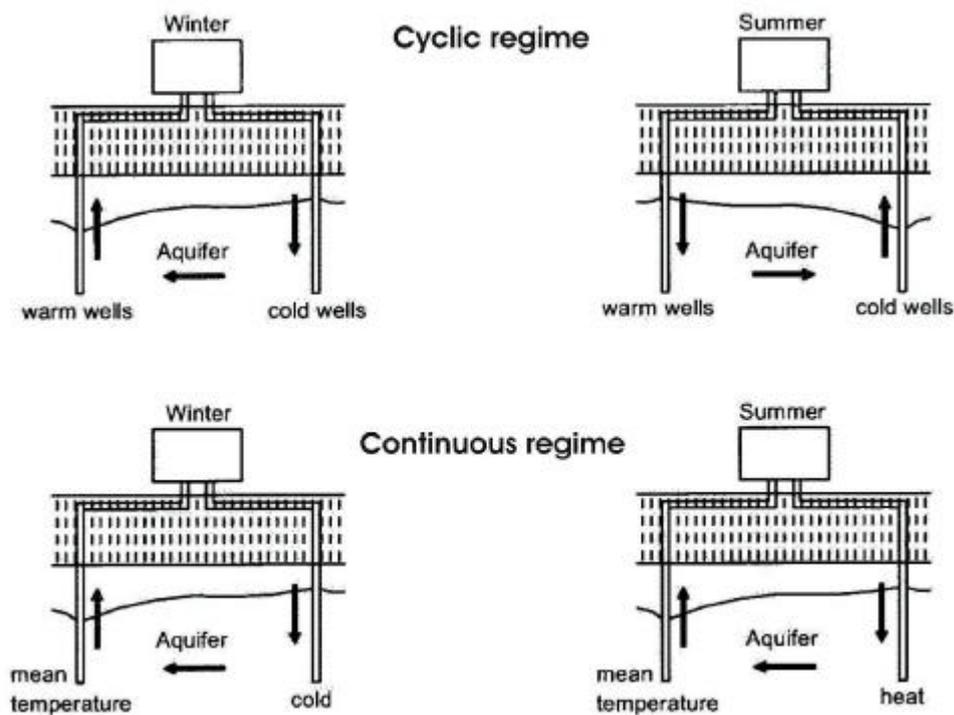


Figure 2. The two basic regimes for Aquifer Thermal Energy Storage (ATES).

Some important parameters for an ATES installation are high ground porosity, medium to high hydraulic transmission rate around the boreholes, but a minimum of ground water flow through the reservoir. Ground water chemistry represents another set of parameters that must be given proper attention in order to prevent scale formation and furring.

Numerous ATES facilities are in operation in Sweden, Germany, The Netherlands, Belgium and some other European countries, including a system for heating and cooling at Oslo hovedflyplass Gardermoen. The Netherlands are probably the technological leaders in the field.

### 3.1.2 Borehole thermal energy storage

Sweden (Lulea Technical University) has been one of the pioneers in developing borehole thermal storage. The first project was designed in order to store waste heat from a steel smelter in Lulea, and use it for space heating at the university.

The holes for BTES are usually drilled to a depth of about 100-200 meters, using mine drilling technology. The drillhole diameter is typically 150-200 mm.

Each hole is furnished with pipes for inserting and extracting a heat/cold carrying fluid into the hole. There are two basic principles, open and closed, being used to transport the heat carrying medium in and out of the holes. The two principles are illustrated in Figure 3.

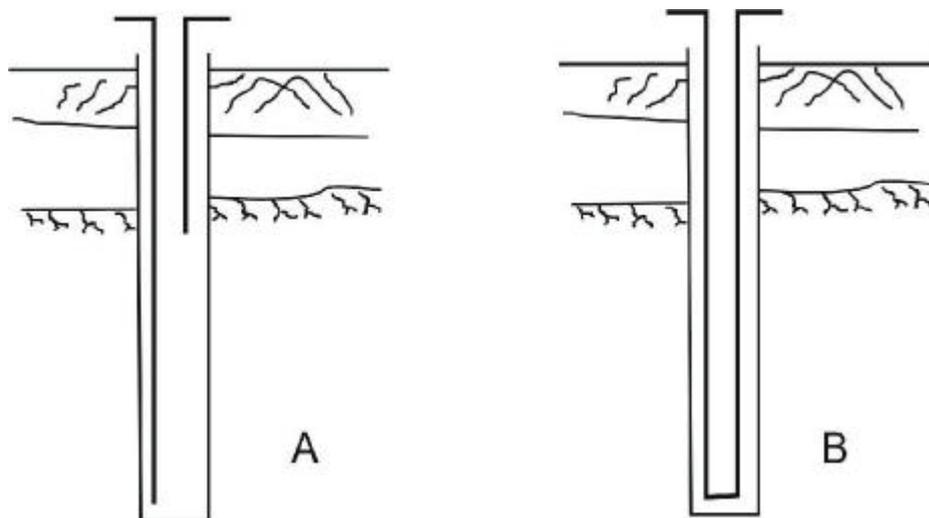


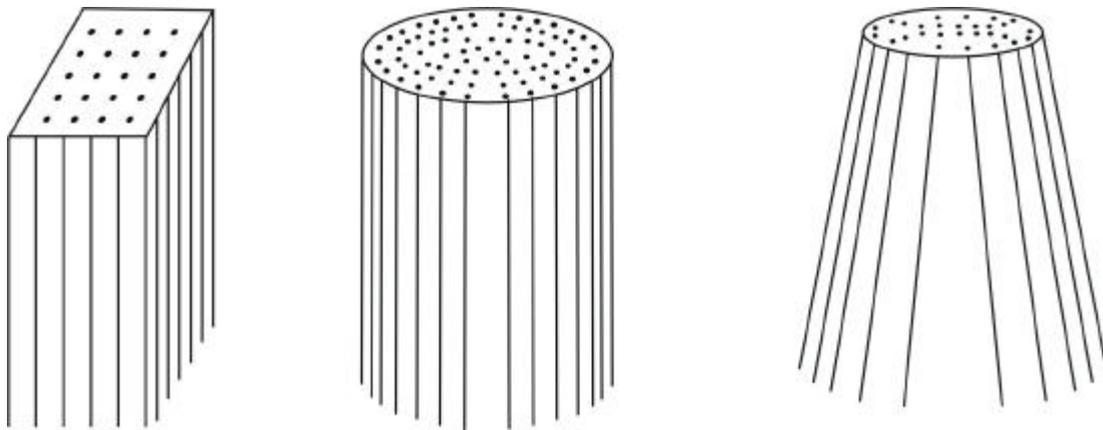
Figure 3. Open (A) and closed (B) in-hole piping systems in Borehole Thermal Energy Storage (BTES).

In the open system is the inserting pipe placed with its outlet close to the bottom of the hole, whereas the extraction pipe has its inlet opening close to the top of the hole, but below the ground water table. The closed system uses u-pipes, and this means that the heat medium is pumped in a closed circuit, eliminating a number of potential problems with regard to water chemistry etc. that are inherent in the open system. The u-pipes act as a heat exchanger between the heat/cold carrying medium and the surrounding rock. Heat transfer between the

u-pipes and the rock is either through water filling the hole, or through some in-filling material like sand, mortar or bentonite clay.

The holes can be drilled either in a quadratic or a hexagonal pattern, and they are usually vertical. A hexagonal pattern is better with regard to energy transmission and heat losses in the rock mass, but a square pattern is simpler to drill and connection between drillholes is easier. The distance between the boreholes will among other factors depend on the thermal properties of the rock. Distances of 6 to 8 meters are quite common in Scandinavian rock types.

The holes can be connected in serial configuration, in parallel, or in a combination serial/parallel depending on the planned thermal loading and unloading of the facility. 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 4.



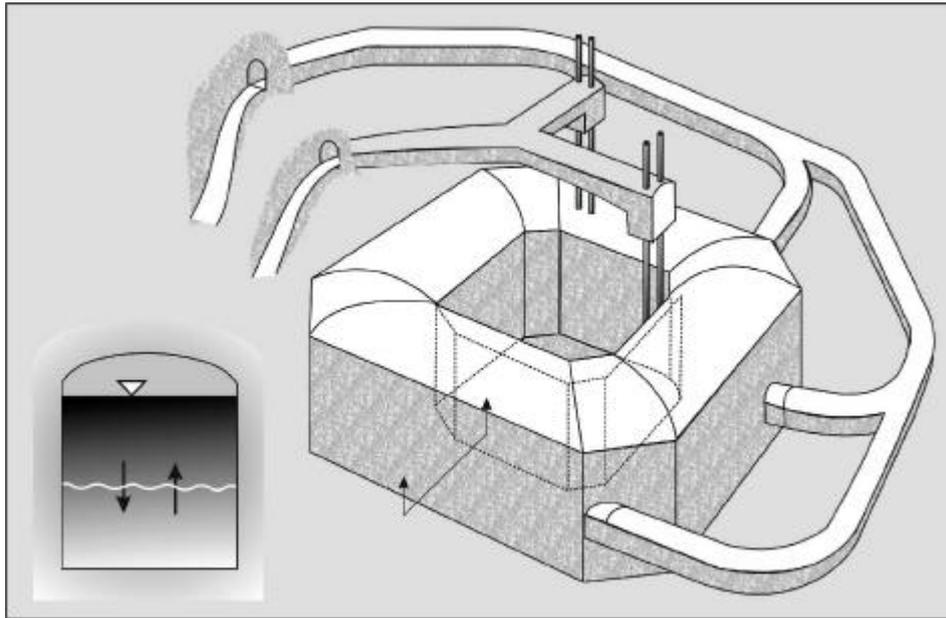
*Figure 4. Examples of different drilling patterns that may be used in a BTES facility.*

Some important parameters for a successful BTES 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.

There are a few BTES facilities in Norway, mainly around Oslo. The newest project is the new Sentralsykehuset i Akershus at Lørenskog. The total installation will encompass 180 holes each with a depth of 200 meters. These holes will be able to supply 3.2 MWh heat during the cold season, and 4.8 MWh will be loaded into the storage from cooling equipment during the summer. This will be the largest BTES installation in Europe (Helgesen, 2002).

### **3.1.3 Cavern thermal energy storage**

There are not too many examples of CTES installations in Europe. One of the more spectacular is the Lyckebo project in Uppsala, Sweden. The facility is used as seasonal storage for a district heating system with solar collectors. The underground excavation has a volume of 100 000 m<sup>3</sup> and is formed almost like a do-nut as shown in Figure 5. This shape has a high volume to perimeter surface ratio that reduces heat loss.



*Figure 5. The cavern thermal energy storage facility at Lyckebo in Sweden.*

The system is designed to supply 550 families with space heating and domestic hot water from a solar collector installation with an area of 4320 m<sup>2</sup>. The system also has an electric boiler for back-up (Many other seasonal stores have back-up heating systems based on electricity, gas or oil). The water in the cavern is inserted and extracted by two telescopic pipes, and this helps to ensure a very good temperature stratification with top and bottom temperatures of 90 °C and 40 °C respectively (Pilebro et al, 1986). (See section 3.2).

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 favourable conditions. A crucial factor is ground water transport through the rock masses in the area, the less the better.

The situation will be a parallel to freeze storage installations, where the cold (heat) loss stabilisation effect has been demonstrated in numerous Norwegian plants (Broch et al, 1994).

### **3.1.4 Ducts in soil**

The ducts in soil concept has found extensive use in connection with ground coupled heat pumps (GCHP) where the duct can be placed in horizontal relatively shallow trenches, or in vertical boreholes. Vertical boreholes are also suitable for thermal storage as discussed above in the section on BTES.

Soil storage with vertical ducts has not been much used in Norway, but about ten installations in soil and clay have been built in Sweden. The active storage volumes vary between 10 000 and 100 000 m<sup>3</sup>. The stores have to be equipped with some sort of insulation over the top part.

This type of storage is best suited for low temperatures around 25-30 °C, and will need heat pumps to raise the temperature of the water used for space heating and tap water to a suitable level.

The low temperature in the store means that it can be combined with solar collectors working at low to medium temperatures. Such collectors are simpler and cheaper than high temperature collectors, and at the same time will the efficiency and practical operating hours increase (Andrén, 2001).

### 3.1.5 Pit storage

There are a number of seasonal pit storage installations for instance in Denmark, Sweden and Germany. The volumes can vary from 1-3000 m<sup>3</sup> for a multi-family dwelling up to more than 10 000 m<sup>3</sup> for housing complexes and commercial buildings. The largest installation in Europe is at present a 12 000 m<sup>3</sup> concrete pit with a stainless steel liner in Friedrichshaven in Germany. This is used to store solar energy from a collector system with an area of 5600 m<sup>2</sup> with a maximum temperature of 95 °C (Lottner and Mangold, 2000).

Figure 6 shows the basic design of a pit storage facility in soil. The store will usually be placed close to the surface in order to reduce excavation costs but it will then need to be insulated both on the top and along the inclined walls, at least down to some depth. The top is usually covered with a load carrying construction (lid), so that the surface area can be used for some purpose or other. The pit also needs to be waterproofed, and this has usually been done by installing a liner of plastic or rubber. The storage temperature can be up to a maximum of 95 °C, provided that the liner is made of either advanced polymer materials or metal.

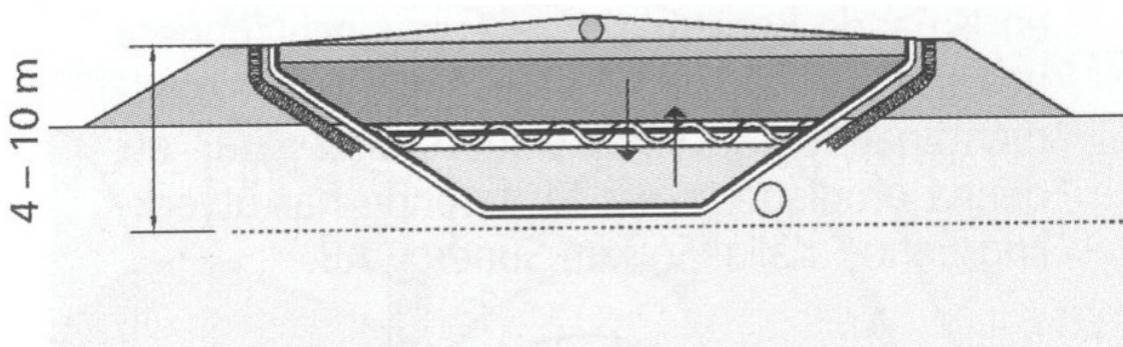
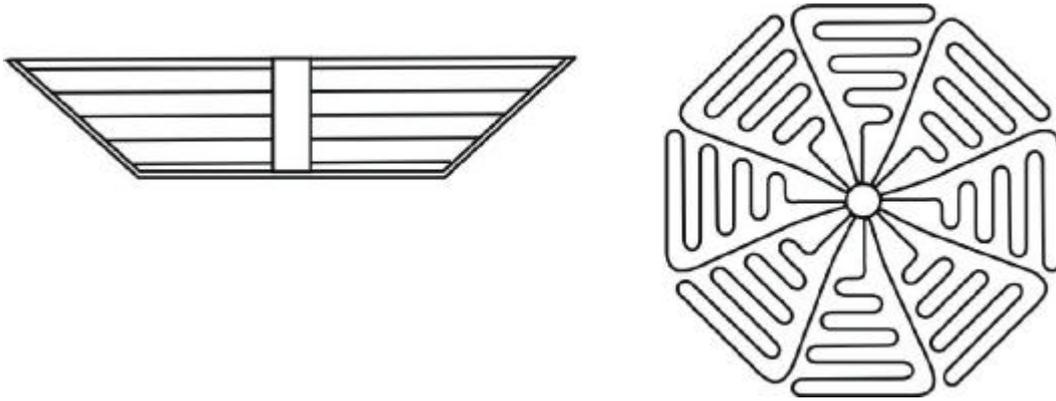


Figure 6. Pit storage facility in soil.

Storage pits are normally filled with water, but there are also examples where the pit is filled with both rock and water, using pipe heat exchangers placed in sand between layers of rock. One such installation, built in connection with a solar heating plant in Denmark is illustrated in Figure 7 (Heller, 2000).



*Figure 7. Pit thermal energy storage filled with gravel/sand and water, and heat exchanger piping. Vertical cross section with pipe layers at left, lay-out of one layer of piping at right.*

The sand layers are used for protection of the PEX polymer pipes which have a total length of 5000 meters. The store volume is 3500 m<sup>3</sup>, and the maximum storage temperature is 66 °C.

Practically all pit storage facilities in Europe are built in connection with solar collector systems for district heating. One interesting exception, however, is the snow storage used for summer cooling at the Sundsvall hospital in Sweden.

The storage is a shallow pit lined with waterproof asphalt, and it has the capacity to store 60 000 m<sup>3</sup> (40 000 tonnes) of snow. The stored snow is covered with a 0.2 m thick layer of wood chips that insulates the snow and reduces the natural melting rates so that some snow remains in the storage during the entire cooling season. Melt water from the storage is pumped to the hospital where it is used for cooling, and afterwards returned to the snow storage. When all the snow has melted, the wood chips are dried and burned in a local heating plant. (Skogsberg and Nordell, 2001)

Based on published information, it seems that all the various pit storage installations are different, but a common problem is water leakage and heat loss due to the fact that a pit storage facility will not be placed deep in the ground due to costs.

### **3.2 Water tanks above ground**

The most common use of water tanks above ground in Europe is in connection with solar collectors for production of warm water for space heating and/or tap water. The main application is in smaller plants for single-family houses. Installations used for tap water production will usually need an auxiliary heat source, for instance gas, biomass or electricity.

When the solar collector is used only to produce tap water, a storage volume of about 50-100 litres per square meter of collector area is normally sufficient. The collector area will be substantially larger in a combined plant for space heating and tap water production, and a suitable storage volume per square meter of collector area will be around 50 litres (KanEnergi, 2001).

Water tanks above ground are also used as a buffer storage in connection with larger solar collector plants where the main storage medium may be for instance a BTES facility for seasonal storage in a district or local heating system.

There are also a few examples of large water tanks being used for seasonal storage.

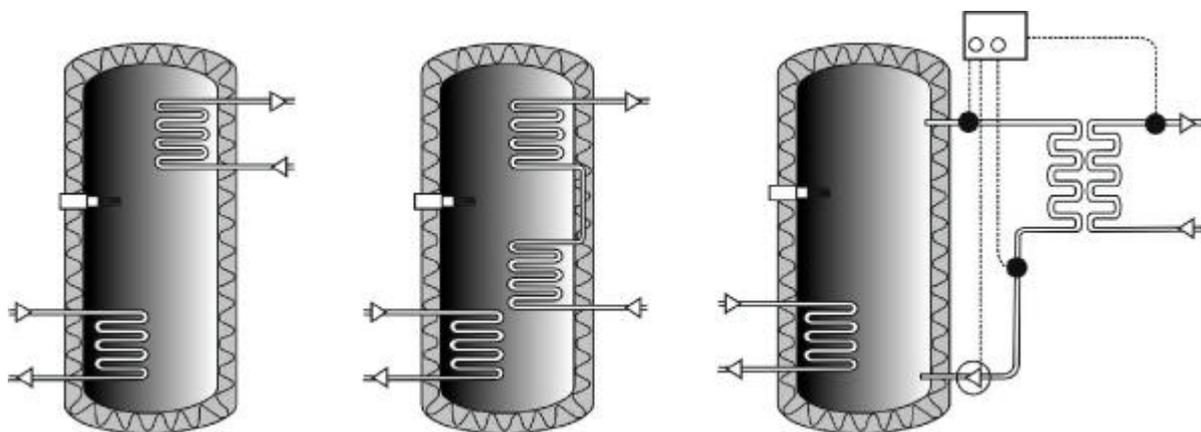
The only application where one can talk about a developed market is in connection with water tanks for smaller solar collector installations. There are a large number of producers in Europe, including some manufacturers of solar collectors. Most of them are small. This means that there is a potential for substantially reduced prices if large-scale, cost effective production can be organised.

Looking at the installation of solar collectors in Europe, Germany has about 40% of the total capacity measured in square meters, Austria and Greece accounts for 20% each, and the remaining 20% is spread throughout the rest of Europe. It seems reasonable to assume that the producers of small water tanks for thermal storage will show a similar geographic distribution.

Larger tanks for either buffer storage or seasonal storage will be manufactured according to order, and the market for such specific applications will probably remain small.

The storage density (energy capacity) for water tanks is in the order of  $0.01 \text{ MWh/m}^3$ .

Referring to the discussion above on the importance of temperature layering, a water storage tank for solar tap water production will achieve a much better layering and higher utilisation factor of the stored heat with two internal heat exchangers instead of one. An even higher utilisation factor can be achieved with an external heat exchanger as illustrated in Figure 8 (Andr n, 2001).



*Figure 8. Storage water tanks for small-scale solar collectors. At left a simple tank with one internal heat exchanger for hot water in the top region. About 40 per cent of the thermal energy can be retrieved. In the middle is a better design with two internal heat exchangers. About 70 per cent of the stored thermal energy can be retrieved. At the right is a tank with an external plate heat exchanger. This design will give the best thermal layering, and up to 80 per cent of the stored energy can be recovered.*

Water or ice tanks are widely used in Japan for thermal storage in connection with the cooling needs in HVAC (Heat-Ventilation-Air conditioning) systems. The most important goal for such systems is peak shifting (Yamaha and Shuku, 2001).

### 3.3 Rock filled storage

Some solar collectors are made to produce hot/warm air instead of water. In this case can the sensible heat be transferred to a storage volume filled with rocks of fairly equal size. Uniform size is necessary in order to avoid channelling and ensure a satisfactory distribution of the air flowing through the storage volume. The storage is usually placed in the basement of a building. The heat capacity in a rock storage facility is about 40% of the heat capacity of water. A rock storage facility must consequently be 2.5 times larger than a water tank for a given collector area (KanEnergi, 2001).

### 3.4 Phase change materials (PCM)

A phase change material melts and takes up energy corresponding to the latent heat of the material when the temperature increases above the melting point. When the temperature decreases below the material's melting point, the PCM solidifies (freezes) and the latent heat is released. 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 °C. The use of PCM for temperature buffering will lead to energy savings, and it is also expected that the thermal comfort will improve (Mehling, 2001). Some application areas for PCM in buildings are illustrated in Figure 9.

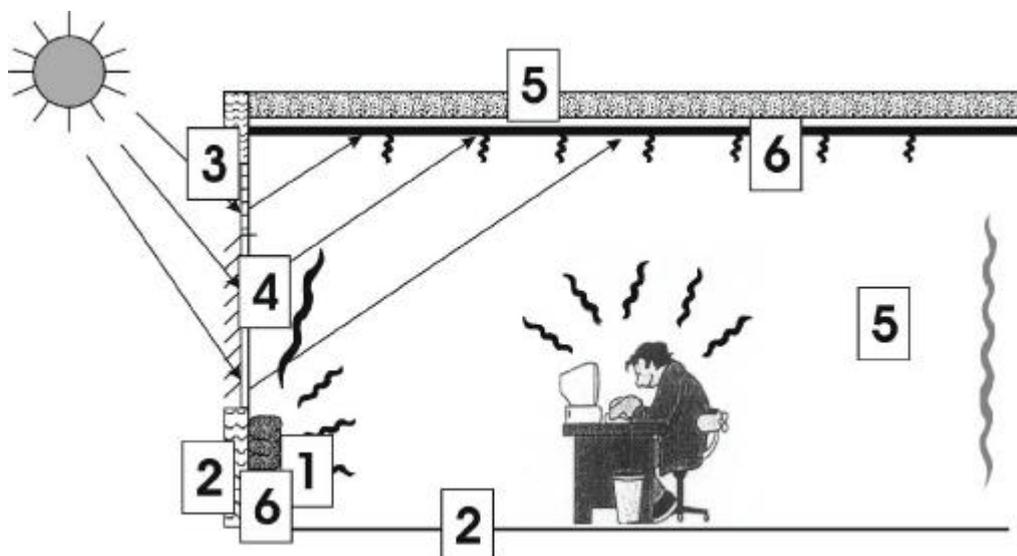


Figure 9. Application areas for PCM in buildings. No. 1: Latent heat store for space heating. No. 2: Plaster and compound systems with high heat storage capacity. No. 3: Transparent insulation and daylighting schemes. No. 4: Shading PCM compounding system. No. 5: PCM in gypsum products and paints. No. 6: PCM to buffer temperature variations in solar-air-systems.

A wide variety of solid-liquid phase change materials is commercially available with temperature ranges from  $-21\text{ }^{\circ}\text{C}$  (sodium chloride solution) to more than  $+200\text{ }^{\circ}\text{C}$  (salts and eutectic salt mixtures).

Some of the more popular and easy to use products are various paraffin and these can be made with melting points between  $-20\text{ }^{\circ}\text{C}$  and  $120\text{ }^{\circ}\text{C}$ . Paraffins are non-toxic, ecologically harmless, and chemically inert to nearly all materials, and this means that there will be no corrosion in heating/cooling systems.

Phase change materials (solid-liquid) have a storage density in the order of  $0.1\text{ MWh/m}^3$ .

The use of a complete solid-liquid-vapour phase change cycle will further increase the storage density. Such systems are technically feasible, but quite a bit more complicated than the simple (and passive) solid-liquid-solid cycle.

### **3.5 Thermochemical storage**

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 vapour to the salt. This concept works “on paper” and in the lab, but there are problems with corrosion and air tightness since the dry salt must be stored in an evacuated (airless) environment. Reactions like these are combined with a heat pumping effect. Energy at a low temperature level has to be provided in order to discharge the storage, for instance vaporisation of water. At the charging process is energy withdrawn from the system for instance by condensing water.

Another reaction is adsorption of water vapour in a zeolite material. Zeolites are alumina silicates with high micro-porosity and open structure. When dry zeolite material comes in contact with water vapour, the water vapour 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  $100\text{ }^{\circ}\text{C}$  when the water is driven off (desorption). The adsorption/desorption processes can be repeated (almost) indefinitely without any significant deterioration of the zeolite material.

This process is being used in a heating/cooling plant in a building in Munich. Drying of the zeolite material is done by cheap, off-peak heat from the district heating system (Hauer, 2001).

There is actually a commercial product based on zeolite/water adsorption available, also in Germany, namely self-cooling beer kegs. The user just turns a handle and waits for about ten minutes. Then can he/she serve 20 litres of cold beer to thirsty guests. The empty kegs are returned to the factory, recharged by heating, and filled with beer again. Since its introduction in 2001, about 20 000 kegs are in regular use (Maier-Laxhuber, 2001)

Thermochemical reactions have the potential to store up to 1 MWh/m<sup>3</sup>, depending of course upon the actual reaction. However, they are more complex than other thermal energy storage systems, but they are also more flexible.

## **4. Interaction with other Smartbuild strategies and technologies**

### **4.1 Thermal storage and user needs**

Thermal energy storage has a number of potential applications, both in single-family houses, housing complexes, and in a wide variety of commercial and service buildings. The users are therefore very different with regard to building ownership, knowledge and competence, financial capacity, environmental engagement, and risk aversion attitudes. The latter is one of the important barriers with regard to development and application of new technology, both among Owners, contractors, users, suppliers and consultants.

However, the users will not express a need or an interest for thermal energy storage capacity *per se*. They will primarily be looking for a certain level of functional and reliable comfort at an affordable cost. Further, affordable cost will also be seen different among different users. Some may chose high investment solutions in return for lower operating costs in the operation phase, perhaps also discounting expected increases in energy prices. Others again will opt for low investment solutions, accepting higher operating costs.

A third group of users will be the ones who rent residential or commercial space owned by someone else. In this case will the user's preferences probably be of little importance.

### **4.2 Thermal storage and environmental criteria**

Norway has become dependent on import of electric energy, and this means importing electric energy generated by burning fossil fuels. In the case of "business as usual" the future increase in the use of electricity will therefore lead to more greenhouse gas emissions caused by Norwegian consumers. It is not obvious that for instance Danish coal fired power plants will continue to "carry" the CO<sub>2</sub> quota for electricity sold to Norway if the Kyoto protocol is implemented internationally.

Thermal energy storage, combined with new renewable energy sources and waste heat/cold recovery, can make a significant contribution with regard to reducing the amount of electric energy used for space heating and cooling today, and this will lead to less greenhouse gas emissions "on the Norwegian account" due to import. A further reduction is possible by replacing space heating plants burning oil.

However, some UTES applications may lead to negative environmental impacts.

A BTES installation with closed loop U-tubes will often use water as the heat exchanger medium with an additive such as glycol to prevent freezing. This can lead to some underground contamination if leakage should occur. This also applies to a duct in soil installation where the dissemination of the polluting medium can become much more wide spread than in a BTES plant.

Also an ATES installation used for heating and cooling can lead to environmental problems due to the pumping of groundwater into and out of the aquifer, or between aquifers as in the Parliament project (refurbished former Reichstag) in Berlin. The exchange of water can disturb the mass balance in the reservoir and lead to groundwater contamination in areas that are outside the zones that are influenced by temperature changes.

A number of PCMs contain one or more chemical components that may lead to negative environmental impacts if they were to be released into air or water.

The same consideration will apply to salts used in thermochemical storage concepts, whereas the use of zeolites is considered to be without any potential negative impacts (Zeo-Tech, 2001).

### 4.3 Thermal storage and indoor environment

Thermal storage will *per se* not have a direct effect with regard to the quality of the indoor environment, but, as discussed in section 3.4 above, PCM materials are being used to buffer significant indoor temperature changes.

### 4.4 Thermal storage and integrated design

The basic elements of integrated design to achieve a comfortable indoor environment can be illustrated as shown in Figure 10. Architectural design strategies will always be the starting point in this process, and the need for technical installations with their complexity, capacity and cost will to a very large degree depend on the success or lack of success of the design strategy.

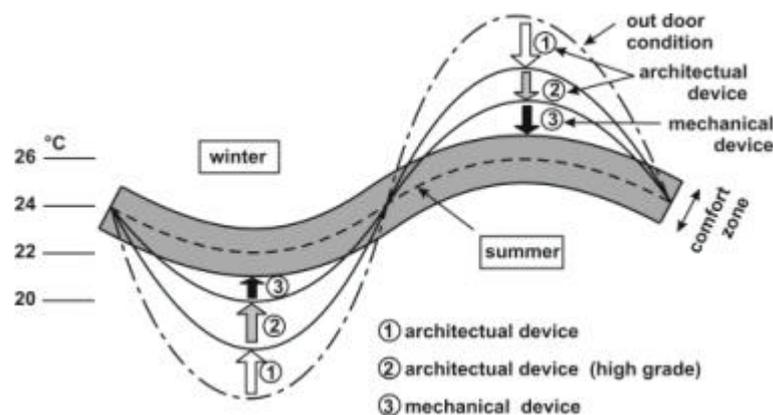


Figure 10. Basic elements for integrated design of building comfort systems. (Narita, 1997).

The principle of thermal storage is already being actively used in many buildings simply by utilising the thermal mass, or thermal capacity of the building itself. One common example is to use the ventilation plant at full capacity during night in order to cool down the building. This can save on peak cooling costs during the day when the building gets gradually warmer. Night operation can in itself also be cheaper due to lower off-peak electricity cost.

Another example is utilisation of passive solar heating.

Using the building mass for thermal storage has the potential of finding much broader application, especially in relatively moderate climates.

The thermal mass of buildings can be enhanced by conscious selection of building materials. The thermal capacity of concrete can for instance be increased by using aggregates with higher specific heat than common rock materials, for instance olivine rock or iron ore.

Phase change materials can also be incorporated in the structure of the building, for instance inside floor/roof elements, or as micro capsules embedded in plaster wallboard, paints, and other surface coatings. This will help to buffer temperature fluctuations for during a normal working day.

#### 4.5 Thermal storage and building integrated energy systems

With today’s uncertainties regarding future energy prices for various carriers, it is not difficult to find positive arguments for flexible comfort systems in the building sector.

A conceptual illustration of an integrated energy system based on new renewable energy sources with thermal storage is shown in Figure 11 (Nielsen et al, 2002). Any particular application may incorporate one or more of the energy sources and system outputs. Buildings have a large mass and will react slowly to changes in heating/cooling demands. The figure therefore indicates the use of local weather forecasts in order to optimise system efficiency and output by proactive rather than reactive control.

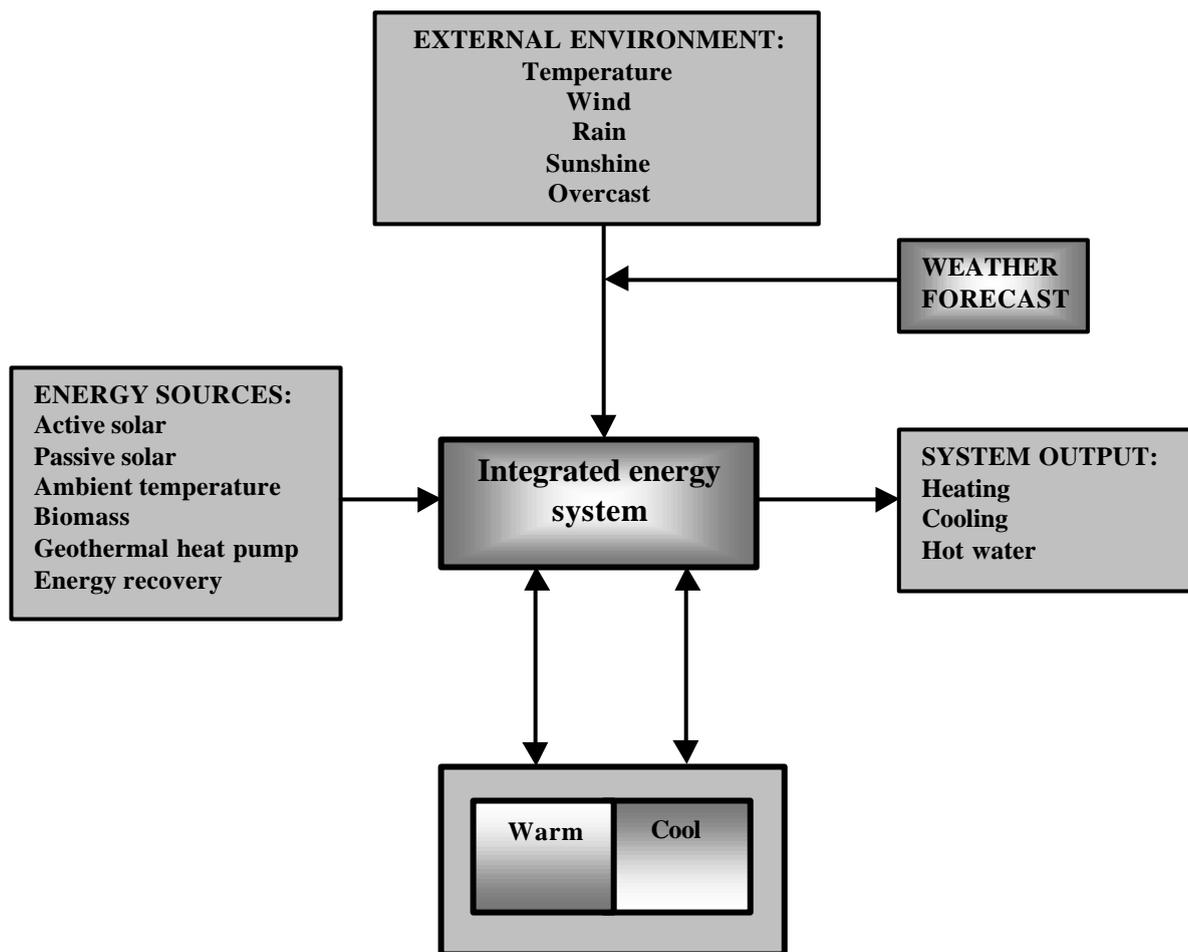


Figure 11. Conceptual illustration of an integrated energy system with thermal storage.

Integrated energy systems need to be developed at two levels:

- Integration of various thermal energy sources into concurrent systems for heating, cooling and production of hot water, eventually incorporating thermal storage.
- Physical integration of such systems into the building structure.

#### **4.6 Thermal storage and lighting systems**

No direct interaction can be envisaged between thermal storage and lighting systems. However, it is a possibility that some solutions for lighting systems, especially architectural design strategies, may contribute also to passive solar heating of the building's thermal mass.

#### **4.7 Thermal storage and building integrated photovoltaics**

Photovoltaic panels need cooling in order to maintain their efficiency. Large panels can be cooled by air flowing in a channel along the back of the panel. Cool air enters at the bottom of the channel and exits at the top at a higher temperature. The thermal energy contained in the warmer air can be stored and used for space heating. Such a concept was described in one of the presentations at the Photovoltaics Seminar at NTNU in June 2000. (No reference available).

The heat can either be stored in a rock storage facility, or converted to water storage via a heat exchanger. It is also possible to integrate a heat pump in this circuit to raise the temperature in the storage. A water storage combined with a heat pump can also produce tap water.

Another example is described in the Smartbuild State of the Art report on Building Integrated Photovoltaics (Andresen, 2002). In this case is a PV/thermal collector system combined with a heat pump and an aquifer. In summer, the PV/thermal collector is cooled with 5-10 °C water from the aquifer. While cooling the collector, the water is warmed to about 20 °C, and stored in the aquifer to be used as a heat source in winter (ATES).

#### **4.8 Thermal storage and heating, cooling and ventilation systems**

In North America it is typically found that a UTES system integrated as part of a building's heating, cooling and ventilation system can reduce cooling costs by 80 per cent and heating costs by 40 per cent or more.

Heating, cooling and ventilation systems should preferably be discussed in connection with the building's energy system, ref. section 4.5 above.

#### **4.9 Thermal storage and heat pumps**

Ground-coupled heat pumps (GCHP) are probably the fastest growing market sector for heat pumps in residential buildings in North America and Central/North Europe. Such installations can be used both for space heating in winter and cooling in summer, simply by reversing the system. This also incorporates an element of thermal storage. When the system is used for heating, the ground around the heat exchanger(s) will gradually cool down, and may eventually freeze if the heat exchanger is placed in soil. Then when the system is reversed for

cooling, the ground gradually warms up, and this heat will be reclaimed during the next winter cycle.

The commercial sector is much more diverse than the residential sector and GCHPs have been used for heating and cooling in offices, schools, supermarkets, shopping centres, hotels, sports complexes, and institutional buildings.

Heat pumps are also being used in connection with ATES systems in the commercial sector.

Heat pumps are further used in connection with seasonal pit storage where they can extract additional thermal heat when the temperature in the store gradually falls below the practical temperature needed by for instance hydronic floor heating (Everett, 2000).

Heat pumps combined with a facility for thermal storage can in some applications be run at an optimum state most of the time. Such a combination may also enable the heat pump to cover a higher percentage of a building's need for space heating and/or cooling.

#### **4.10 Thermal storage and operation and automation**

Thermal storage installations in hybrid heating/cooling comfort systems will need quite sophisticated building energy management systems (BEMS) in order to realise their full potential. Such systems will encompass both hardware and software items.

The thermal inertia of buildings is quite substantial as discussed above in connection with integrated design. It will therefore be beneficial from economic and energy conservation points of view, to develop proactive management systems with input from outdoor sensors and local weather forecasts, as well as indoor monitoring data. Using local weather forecasts has been demonstrated by various projects, among others in Sweden (Johansson, 1999).

#### **4.11 Thermal storage and implementation strategies**

As discussed in the previous Section 2 Central concepts, can active thermal energy storage be used for peak shaving/shifting in electric grids and district heating systems. This has been one of the important drivers in Japan, where an increasing number of installations with ice or water tanks, natural and man-made aquifers, and building integrated PCMs are in operation.

Differentiated rates for electricity and district heating have proven to be quite effective in order to encourage development and implementation of peak shifting measures (Setterwall, 2000). This can save investment in new transmission capacity for the utilities, but differentiated rates are primarily a function of the operating characteristics of generating plants based on fossil fuels. As opposed to hydroelectric plants, thermal power plants must be run on peak capacity in order to keep costs down.

Differentiated rates are therefore not a relevant driver in the Norwegian market. Further, the Norwegian distribution grid is claimed to have sufficient local capacity to accommodate peak loads also in the winter, so peak shaving is of little or no economic value to the grid owners.

It still remains a fact that Sweden, as opposed to Norway, has built a number of different storage facilities such as caves, pits, ducts in soil, and borehole storage, even if the Swedish utilities do not offer the consumers lower power rates during the night.

It is, however, not within the scope of this state-of-the-art report to try to analyse and describe the reasons behind the Swedish "success" in this field, and discuss their relevance for Norwegian conditions. An eventual analysis will belong within the framework of WP 1.

Implementation of thermal energy storage in the Norwegian market will at the first instance depend entirely on how other subtasks in WP 2 and WP 3 find it technically and economically possible and beneficial to incorporate thermal storage in their designs. Further development towards real life implementation will be supported by the different subtasks in WP 1, but basically can four lines of activities be envisaged:

- Inform and educate customers (end users, architects, consultants, developers etc.)
- Minimise potential technical problems through good design and testing
- Develop markets
- Educate the public sector with national and local governments, planners, regulators etc.

## 5. Thermal storage and Smartbuild

The group that rehabilitated and developed the Klosterenga property in Oslo did focus on making an eco-efficient apartment complex integrating various solutions, including a roof mounted solar collector and a thermal storage tank with water. The group was less concerned with minimising costs than finding environmentally sound solutions. However, in spite of this lack of narrow economic focus, all apartments had been sold before rehabilitation was finished and people could move in. It was obviously the total concept with its green profile that attracted buyers, and not the choice of conventional design and cheap solutions (Monsen, 2002).

Perhaps does the field of environmentally friendly buildings have too many bean counters, macro economists, and cost effective engineers, and too few visionaries? Leaders who motivate and inspire change are especially important tools to facilitate eco-industrial development. An open mind, a belief in science and technology and a sense of vision are vital.

The application of thermal energy storage methods will be of most interest in connection with integration of several sources of energy together with various technological solutions e.g. waste heat recovery in combination with heat pumps. Such hybrid systems can replace or supplement conventional solutions for space heating and cooling based on electricity and/or fossil fuels.

Thermal storage can be used both for air-based systems (ventilation) and hydronic comfort systems.

Thermal storage concepts are therefore not an isolated technology with regard to Smartbuild, but development will depend on to which degree other actors in Smartbuild are interested in multi-source hybrid comfort systems.

However, we believe that Smartbuild will loose some of its long-term vision if the work is concentrated on development and extension of today's common practice and well known technology.

Smartbuild should leave room and opportunity for playing with new ideas and untraditional solutions, and not stop such activities by making comments such as: "It's too expensive" or "It's too difficult".

*Playing 100 per cent safe at all times will not lead to progress!*

## 6. Literature, central R&D institutions, and industry

### 6.1 References

Andrén, L. (2001). Solar energy. Practical implementation in buildings. AB Svensk Byggtjänst. ISBN 91-7332-967-3. (Swedish text).

Andresen, I. (2002). Building Integrated Photovoltaics in Smart Energy-Efficient Buildings. A State-of-the-Art. Report. Smart Energy-Efficient Buildings Research Program at NTNU and SINTEF 2002-2006. Trondheim, December 2002.

Broch, E. et al (1994). Storing food and drinking water in rock caverns in Norway. Proc. '94 International Symposium for Grain Elevator and Underground Food Storage, pp. 263-291. Seoul, Korea.

Everett, B. (2000). Solar thermal energy, pp.62. In: Renewable Energy. Power for a Sustainable Future, Chapter 2. Editor: G.Boyle. Oxford University Press in association with The Open University, Milton Keynes, UK. ISBN 0-19-856451-1.

Hauer, A. (2001). Thermal energy storage with zeolite for heating and cooling applications. Proc. ZAE-Symposium 2001. ZAE Bayern (Zentrum für angewandte Energieforschung). TU Bayern, Garching, Munich. (Presentation 14).

Helgesen, R. Geoenergi AS, Nydalen, Oslo. (2002). Private communication.

Heller, A. (2000). Development of seasonal storage in Denmark. Status of storage programme 1997-2000. Proc. TERRASTOCK 2000, 8<sup>th</sup> International Conference on Thermal Energy Storage, pp. 47-52. University of Stuttgart, Stuttgart, Germany.

Johansson, M. (1999). Local weather forecasts control the HVAC system in buildings. CADDET Newsletter No. 4, December 1999, pp.4-5.

KanEnergi (2001). New renewable energy sources. Published by the Norwegian Research Council, Oslo. ISBN 82-12-01621-8. (Norwegian text).

Lottner, V. And Mangold, D. (2000). Status of seasonal thermal energy storage in Germany. Proc. TERRASTOCK 2000, 8<sup>th</sup> International Conference on Thermal Energy Storage, pp. 53-60. University of Stuttgart, Stuttgart, Germany.

Maier-Laxhuber, P. (2001). Cold storage with zeolite systems. Proc. ZAE-Symposium 2001. ZAE Bayern (Zentrum für angewandte Energieforschung). TU Bayern, Garching, Munich. (Presentation 6).

Mehling, H. (2001). R&D project "Innovative PCM-technology". Proc. ZAE-Symposium 2001. ZAE Bayern (Zentrum für angewandte Energieforschung). TU Bayern, Garching, Munich. (Presentation 10).

Monsen, P. K. (2002). Architectural integration of solar energy. Printed presentation at the Industry Workshop, Task 26 Solar Combisystems, IEA Solar Heating & Cooling Programme.

Oslo, Norway. (Compiled by W. Weiss. Arbeitsgemeinschaft ERNEUBARE ENERGIE, Gleisdorf, Austria.

Narita, K. (1997). Meaning of heat (energy) storage. Proc. MEGASTOCK'97, 7<sup>th</sup>. International Conference on Thermal Energy Storage, pp. 1-6. Hokkaido University, Sapporo.

Nielsen, K. Et al (2002). Enviro-Core: A new concept for thermal storage, energy conservation and waste reduction in the building industry. Proc. 1<sup>st</sup> International Conference on Sustainable Energy Technologies, pp. BE 39-43. University of Porto, Porto, Portugal.

Pilebro, H. et al (1986). The Lyckebo project - Thermal energy storage in a rock cavern. Proc. International Symposium on Large Rock Caverns, pp. 549-556, paper A1.12. Ed.: Sari, K. H. O. Helsinki, Finland. Pergamon Press, Oxford, UK.

Setterwall, F. (2000). Annex 10 - Phase change materials (PCM) and chemical reactions for thermal energy storage (TES). Proc. TERRASTOCK 2000, 8<sup>th</sup> International Conference on Thermal Energy Storage, pp. 13-16. University of Stuttgart, Stuttgart, Germany.

Skogsberg K. and Nordell, B. (2001). Cold Regions Science and Technology, 32, pp. 63-70.

Zeo-Tech (2001). [www.zeo-tech.de](http://www.zeo-tech.de)

## 6.2 Sources

Dincer, I. and Rosen, M.A. Thermal Energy Storage. Systems and Applications. Wiley and Sons Ltd. West Sussex, UK. 2002. ISBN 0-471-49573-5-

International Energy Agency (IEA). Implementing Agreement (IA) on Energy Conservation through Energy Storage (ECES). <http://cevre.cu.edu.tr/eces/>

The Australian Co-operative Research Centre for Renewable Energy (ACRE). <http://www.acre.murdoch.edu.au> (See note on co-operative research centres at end of text).

Proceedings. MEGASTOCK'97. 7<sup>th</sup> International Conference on Thermal Energy Storage. Editors: K. Ochifuji and K. Nagano. Hokkaido University, Sapporo, Japan.

Proceedings. TERRASTOCK 2000. 8<sup>th</sup> International Conference on Thermal Energy Storage. Editors: M. Benner and E.W.P. Hahne. University of Stuttgart, Stuttgart, Germany.

Proceedings. 1<sup>st</sup> International Conference on Sustainable Energy Technologies. Porto, Portugal, 2002. Editors: A. Oliveira, C. Alfonso and S. Riffat. University of Porto, Faculty of Engineering, Porto, Portugal, and University of Nottingham, School of the Built Environment, Nottingham, UK.

Rosén, B. et al. Systems for ground source heat and cold - State of the Art. Swedish Geotechnical Institute, Linköping, Sweden. Report No. Varia 511. 2001. (Swedish text).

## 6.3 Central R&D institutions

Tekniska Högskolan i Luleå, Luleå, Sweden (BTES, Pit storage)

Kungliga Tekniska Högskolan, Stockholm (PCM)

Danmarks Tekniske Højskole (Pit Storage)

TU Delft, Netherlands (Heat pumps. BEMS)

Fraunhofer-Institut für Solare Energiesysteme ISE, Freiburg, Germany (PCM)

#### **6.4 Industry**

Statsbygg.

#### **6.5 Note on Co-operative Research Centres (CRC)**

Australia has introduced a new way to organise research activities called Co-operative Research Centres (CRC). The centres are financed by grants from the Federal Government, and State or Territory governments may also contribute to financing. Industry can contribute either by paying directly for specific tasks, or may contribute in kind by allocating staff and other resources to work for the centre.

The formation of such a centre starts with the Government inviting all relevant R&D institutions to draw up plans for a centre that shall work on a specific task. The basic idea is to make the usually fragmented R&D community join forces and engage with industry and other organisations to form networks of co-operation. It often happens that various groupings are formed competing for the project. Each group submits a proposal describing who they are, their own resources relevant to the topic in question, how they plan to spend the government funding and other contributions, and the expected outcome. The process is rather similar to bidding for a building contract based on functional specifications.

This may not seem so different from for instance the Smartbuild group applying for a grant from NFR. However, the main difference is that in this process, the project description is made and the initiative taken by the applicant to suite their competence profile and not to accommodate a need on a national level. The NFR process has little incitement for networking across institutional barriers.