Fig. 1: Construction of the 100 m^3 buffer tank as diurnal storage for the central solar heating plant in Crailsheim, Germany

Fig. 2: Installation of solar collectors on the noise protection wall in Crailsheim Germany, altogether 3,500 m ^{2}

Seasonal storage – a German success story

The German government funded nine research and demonstration plants for solar assisted district heating with seasonal thermal energy storage in the last ten years. Two new plants are under construction. A close look at the German experience with seasonal storage projects is profitable for the future of this technology.

Research on storing solar thermal energy seasonally was first put into a strategic action plan in Sweden in the beginning of the 1980s. Through an international collaboration via the International Energy Agency (IEA) seasonal thermal energy storages found their way through a part of Europe. The first pilot storages were built as research installations in Sweden, Denmark, the Netherlands, Switzerland, Italy, Greece and 1984 in Stuttgart, Germany. While most of these countries stopped their research programmes for seasonal thermal energy storages, in 1993 Germany raised the R&D-programme Solarthermie-2000 and the successor Solarthermie2000plus, that is implemented by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU).

Fig. 3: Germany´s largest solar city: the central solar heating plant with seasonal heat storage in Neckarsulm-Amorbach *Photos (10): Solites*

With support from these programmes nine research and demonstration plants for solar assisted district heating with seasonal thermal energy storage have been built in Germany since 1996 (see table 1). The new projects in Crailsheim and Munich will start operation before summer 2007. Further plants are under realization or in development. The currently largest plant is situated in Neckarsulm and comprises a collector area of 5,470 m^2 and a volume of the seasonal heat storage of 63,000 m^3 ground (Figure 3).

Solar heat cost for the new plants are calculated to 24 €ct/kWh for Munich and 19 €ct/kWh for Crailsheim (without VAT and subsidies). This means, for only twice the price of fossil fuel costs the CO_2 emission of entire urban areas can be reduced to a half! To reach this goal, also other sustainable energy technologies like passive houses, combined heat and power production or biomass combustion are available. Depending on the distinctive prerequisites of every single project, solar assisted district heating with seasonal storage shows excitingly often competitiveness to these measures. Two main reasons are responsible for that: The large size of the system causes price reduction effects and the engineering progress, that could be obtained by the R&D-programmes, leads also in storage technologies to substantial cost reductions.

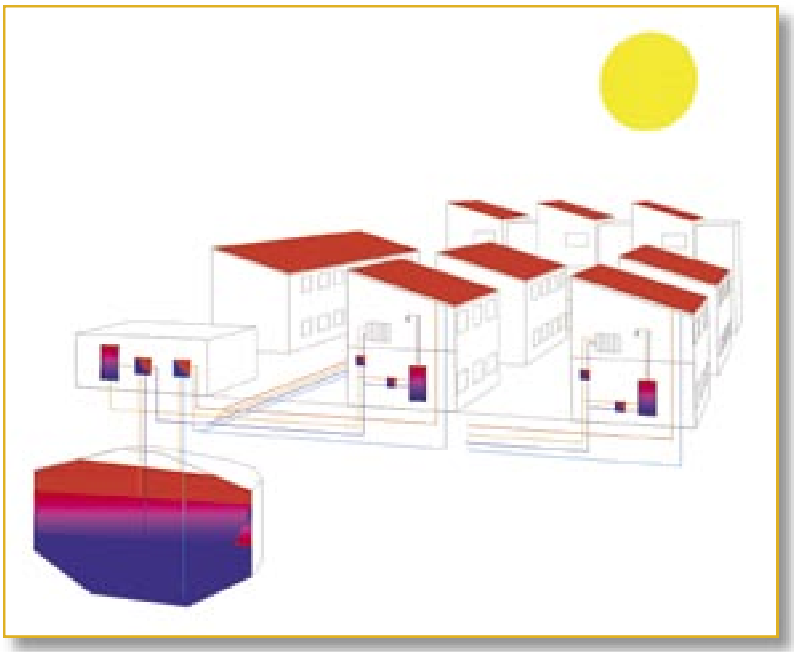


Fig. 4: Scheme of a central solar heating plant with seasonal storage

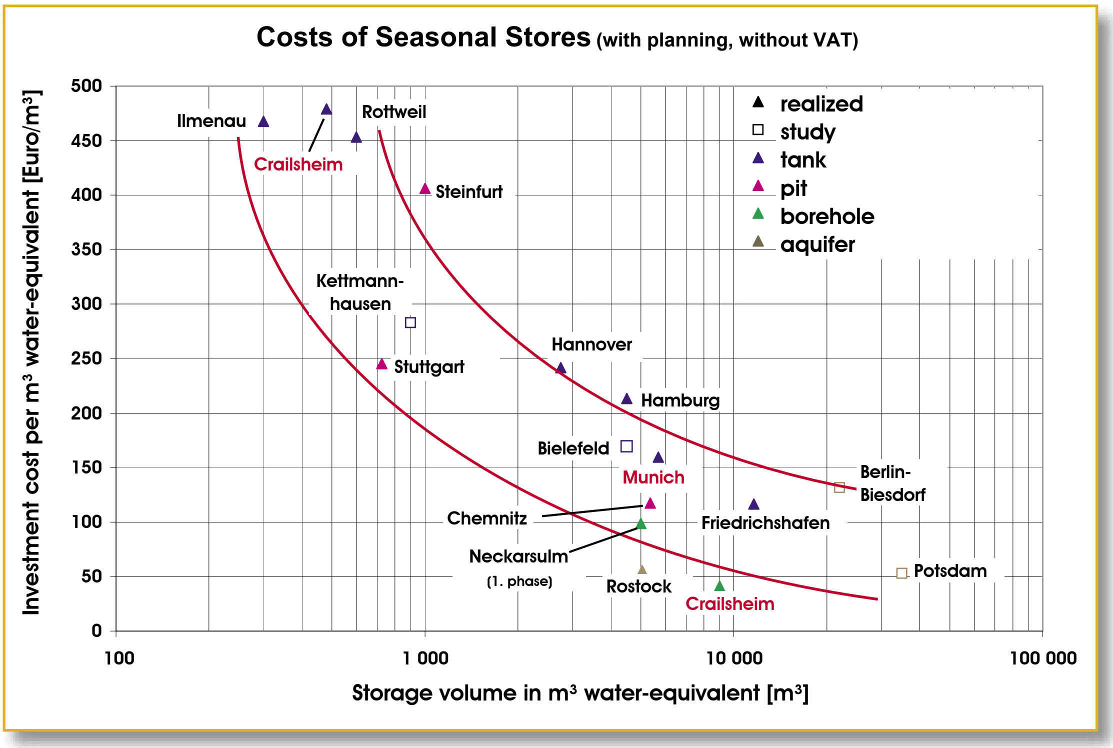
Figures (6): Solites

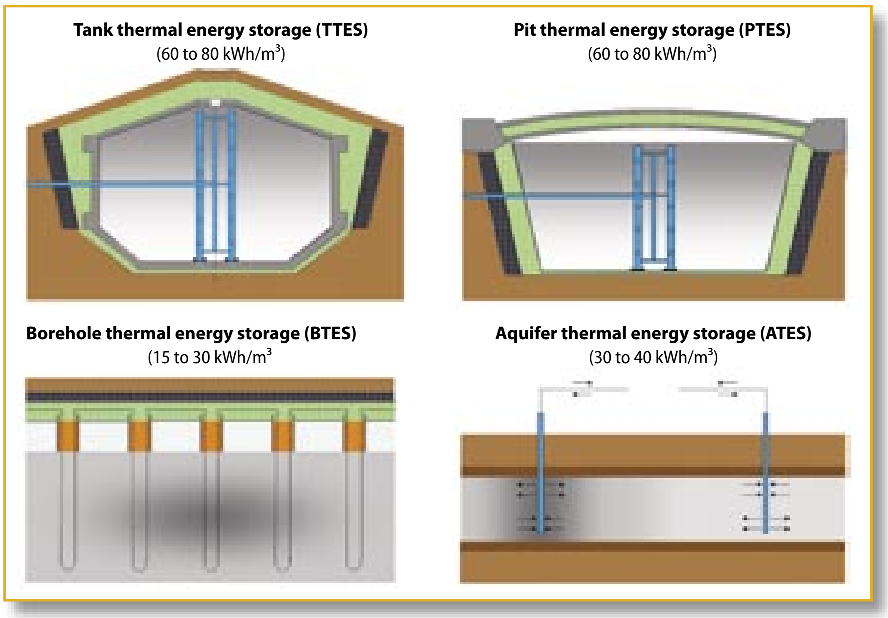
Central solar heating plants

Most of the existing pilot seasonal heat storages are integrated in central solar heating plants (Figure 4). These large systems are the most economic opportunity to provide solar thermal energy in housing estates for the support of domestic hot water preparation and room heating. In case a seasonal heat storage is included in the plant, over 50 % of the fossil fuel demand of an ordinary district heating plant can be replaced by solar energy. The seasonal heat storage is included in the plant to store solar thermal energy during summer and provide solar energy also through the heating period in winter.

Block or district heating systems consist of a heating central, a heat distribution network and heat transfer substations in the connected buildings. Centralized heat production offers high flexibility concerning the choice of the type of energy used. It allows the application of a seasonal storage in an energy- and cost efficient way.

Fig. 5: Specific storage costs with planning, without VAT. The storage costs include costs of charging devices, connecting pipes from the storage to the heating central and planning costs. The specific storage costs are related to the water equivalent storage volume. Moreover, system costs like costs for heat pumps are not considered. BTES = Borehole thermal energy storage, ATES = Aquifer thermal energy storage




Tank thermal energy storage (TTES)
(60 to 80 kWh/m³)

Pit thermal energy storage (PTES)
(60 to 80 kWh/m³)

Borehole thermal energy storage (BTES)
(15 to 30 kWh/m³)

Aquifer thermal energy storage (ATES)
(30 to 40 kWh/m³)

Fig. 6: The four technologies for storing solar thermal energy seasonally

Solar assisted district heating systems are differentiated in systems with short-term or diurnal heat storage, designed to cover 10 to 20 % of the yearly heat demand for room heating and domestic hot water preparation by solar thermal energy, and solar systems with seasonal heat storage with solar fractions of 50 % and higher. The so called solar fraction is that part of the yearly energy demand that is covered by solar energy.

To gain solar thermal energy large collector areas are installed on buildings that are preferably near to the heating central. The heat obtained from the collectors is transported via a solar district heating net to the heating central and is directly distributed to the buildings. The surplus heat of the summer period is fed into the seasonal heat storage. All over Germany the sun provides over two third of its yearly energy supply only during the summer period. Thus during the room heating period, when an ordinary residential house needs more than 80 % of its yearly energy demand, the sun provides not sufficient energy for higher solar fractions. With the beginning of the room heating period, the seasonal heat storage delivers solar thermal energy that is transported to the houses via the district heating net.

Decisive for the optimum function of the solar system is its correct integration into the conventional heating system and the careful design of the solar part as well as of all other components for heat supply: district heating network, heat transfer substations and building services.

Storage size does matter

Most of the common storages accumulate thermal energy as sensible heat in a volume of water. This water is heated up almost to the boiling point of 100 °C. While storing solar thermal energy from summer until winter the storage itself looses a part of the stored energy by heat losses through the surface. Though the storage is heat insulated very well, heat losses occur due to the fact that the maximum temperature in the storage is usually quite high (up to 98 °C) and that this temperature has to be hold in the storage for months (e.g. from July until November).

A characteristic figure for the ratio of the heat losses to the amount of stored energy is the surface/volume ratio: the amount of the energy, that is stored in the volume of the storage, looses heat through the surface.

Thus a small storage with a volume of e.g. 20 m³ has a surface to volume ratio that is eight times the ratio of a storage with 10,000 m³. Hence the heat losses referred to the stored energy are eight times higher for the small storage compared to the large one. That is the reason why storing solar thermal energy seasonally with sensible heat starts to be energy efficient with a storage volume of 1,000 m³ of water or more.

Storage costs

Figure 5 presents the cost data of the built pilot and demonstration plants of table 1 and of studies. The strong cost degression with an increasing storage volume is obvious. Additional costs can arise especially for borehole and aquifer storages for site exploration. High maintenance costs have to be taken into account for water treatment in aquifer storages, if necessary (types of storage see below).

The economy depends not only on the storage costs, but also on the thermal performance of the storage and the connected system. Therefore each system has to be examined separately. In this context important parameters are the maximum and minimum operation temperatures of the storage and of the district heating net. Obviously heat from the storage can only be used without a heat pump as long as the storage temperature is higher than the return temperature of the district heating system. To determine the economy of a storage, the investment and maintenance costs of the storage have to be related to its thermal performance. This quantity is equivalent to the cost of the usable stored energy.

Seasonal heat storages

During the past ten years of research on seasonal storage technologies four different types of storages turned out as main focus for the ongoing engineering research. Figure 6 gives an overview for these storage technologies. They are explained in detail in the following. The decision for a certain type of storage mainly depends on the local prerequisites like the geological and hydrogeological situation in the underground of the respective construction site. Above all an economical rating of possible storages according to the costs for a kWh of thermal energy that can be used from the storage allows the choice of the best storage technology for every single project.

Tank thermal energy storage

A tank thermal energy storage is built as steel or reinforced pre-stressed concrete tank, and as a rule, partially built into the ground. The storage volume is filled with water as storage medium.

The first pilot storages are in operation in Hamburg and Friedrichshafen since 1996. The storages are built as a reinforced pre-stressed concrete tank; they are heat insulated only on the roof and in the vertical walls and are lined with watertight 1.2 mm stainless steel sheets.

The cost analysis of the two plants in Hamburg and Friedrichshafen showed that the stainless steel liner is quite expensive (Figure 5). With the storage in Hannover-Kronsberg a new construction concept was tested to avoid the liner. The wall is made of high density reinforced concrete which exhibits a negligible water diffusion rate even at hot water temperatures. Extensive preliminary investigations have been carried out to test new concrete material compositions which are suitable for the required conditions (temperature, mechanical stress). In comparison to the first storages in Hamburg

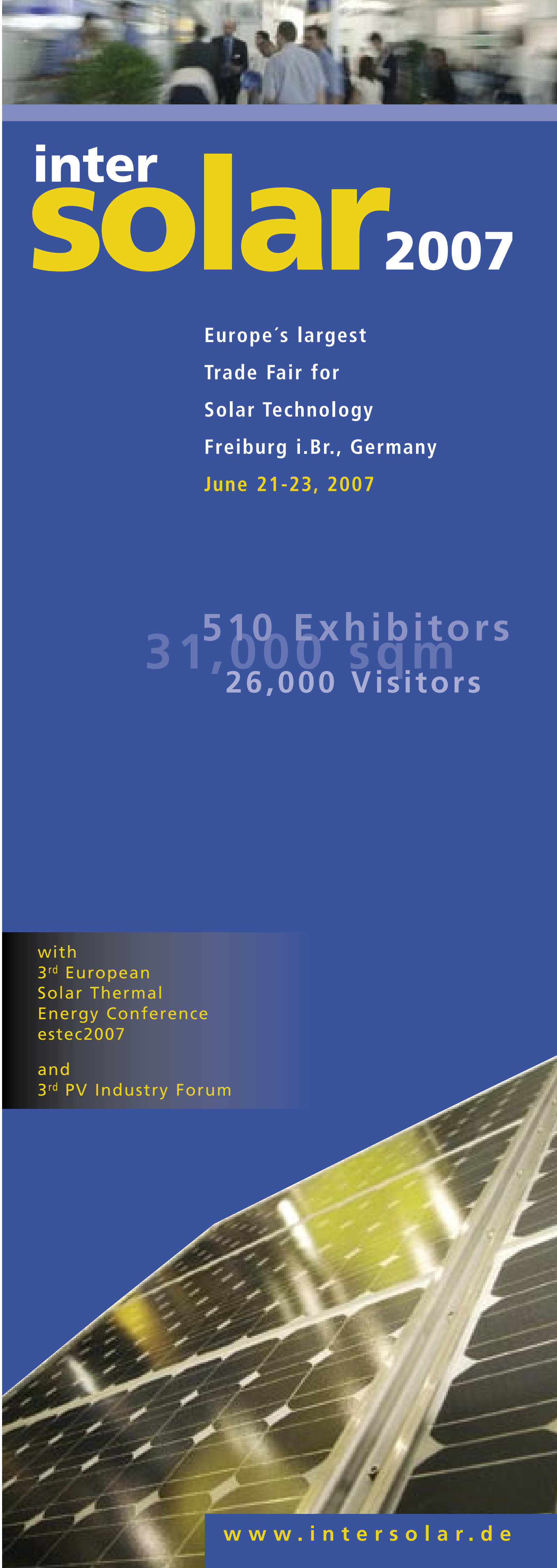


Fig. 7: Sequence of the construction of the tank thermal energy storage in Munich, 2006

Base plate of the storage in shape of the frustum and scaffold

Placing of the prefabricated concrete wall elements, height 9.50 m, thickness of wall 16 cm

Closing of the roof with prefabricated concrete elements, all elements were pre-stressed

Membrane casing with 30 to 70 cm thick heat insulation of expanded glass granules

Modelling of the storage hill with ground

and Friedrichshafen the avoidance of the stainless steel liner leads to a certain water vapour transfer through the concrete material. Consequently the entire construction from the concrete wall to the surrounding ground has to be open for water vapour diffusion in order to avoid water condensation in the insulation. Because of this, amongst others, the insulation is protected from the water that can occur in the drainage with a watertight plastic layer that is open for vapour diffusion from the insulation to the surrounding drainage. Due to the amount of necessary steel reinforcement in the concrete and the complex treatment of the high density concrete the expected cost savings could not be reached in practise.

The new storage in Munich goes one step forward in cost and energy efficiency: The development of the storage concept was finalized in 2000, considering the four main concepts that were in use in Germany so far (tank, pit with gravel/water filling, borehole (BTES) and aquifer (ATES) thermal energy storage). ATES and BTES require special underground conditions that are not available at the site. During project development it was found out that the requirements regarding temperature stratification and capacity rate for charging and discharging can be best satisfied by a tank thermal energy storage.

Figure 7 gives a short sequence of the construction of the storage: The frustum at the bottom were built onsite while the side walls and the roof were built of prefabricated concrete elements that have a stainless steel liner at the inner surface. The steel liners were mounted in horizontal directly after the production of the concrete elements. The wall elements were pre-stressed by steel cables after their installation and the stainless steel plates were welded together to ensure water- and vapour-tightness.

The storage is heat insulated at the side walls and on top by expanded glass granules with a minimum thickness of 30 cm on bottom and a maximum thickness of 70 cm on top of the storage. A vertical drainage protects the insulation from moisture. The bottom of the storage is heat insulated by a 20 cm layer of foam glass gravel because of its higher stability against static pressure. The storage is equipped with a stratification device to enhance temperature stratification and thereby the usability of the accumulated heat. In the end the storage will be visible as a green hill that serves as a playground for children and to toboggan in winter.

The specific investment cost of this storage construction is expected to be significantly lower compared to those of the tank storages in the projects Friedrichshafen, Hamburg and Hannover, although it has an improved heat insulation and a stratification device. The cost reduction can be obtained mainly due to material savings in the concrete construction and the cost effective mounting on site by using prefabricated elements.

Another new concept for tank thermal energy storages is a cylindrical tank made of glass fibre reinforced plastics. The compound wall consists of outer reinforced plastic liners with integrated heat insulation. The construction technology was developed under the guidance of the Technical University of Ilmenau. Today this

Project	Collector area at present (design value) [m^2]	Type of storage	Volume of storage [m^3]	Volume of storage in water equivalent [m^3]	Max. design temperature [°C]	Start of operation
Hamburg-Bramfeld	3,000	concrete tank with stainless steel liner	4,500	4,500	95	1996
Friedrichshafen-Wiggenhausen	4,050 (5,600)	concrete tank with stainless steel liner	12,000	12,000	95	1996
Hannover-Kronsberg	1,350	concrete tank without liner	2,750	2,750	95	2000
Munich-Ackermannbogen	2,900	concrete tank of prefabricated sections with stainless steel liner	5,700	5,700	95	2007**
Solaris-Chemnitz	540*	pit storage with gravel/water filling and plastic liner	8,000	5,300	85	1997
Steinfurt-Borghorst	510	pit storage with gravel/water filling and doubled plastic liner	1,500	1,000	90	1998
Eggenstein-Leopoldshafen*	1,500	pit storage with water filling and plastic liner	3,000	3,000	90	2007**
Neckarsulm-Amorbach	5,470 (6,000)	borehole thermal energy storage with PB-ducts	63,300	20,000	85	1997
Attenkirchen	800	borehole thermal energy storage with inner concrete tank	10,000	4,000	85	2002
Crailsheim	5,470 (7,300)	borehole thermal energy storage with PEX-ducts***	37,500	10,000	85	2007*
Rostock-Brinckmanshöhe	1,000	shallow aquifer storage	20,000	5,000	50	2000

Table 1: Seasonal solar thermal energy storage projects in Germany. The heat capacity of 1 m^3 of storage material differs depending on the material itself. Thus the volume of the storage is converted into a volume of water equivalent comprising the same heat capacity as the realized storage volume.

*** vacuum tubes, ** planned, *** cross-linked polyethylene**

Source: Solites

type of storage is available by the industry not only for large storage volumes, but also for small ones (*www.ichbin2.de*).

Pit thermal energy storage

The usually naturally tilted walls of a pit are heat insulated and then lined with watertight plastic foil. The storage is filled with water and a heat insulated roof closes the pit. The roof can be floating on the water like in the storages in Denmark (Ottrupgard and Marstal, see page 58) or is built like a self supporting structure as a rugged roof. The design of the heat insulation system of the bottom, the walls and the roof, possible materials for the watertight plastic foils and construction technologies for the roof are – amongst others – research agenda of an ongoing research project at the ITW of Stuttgart University.

Due to the fact that the construction of the roof over the storing »lake« is difficult and might be quite costly, the first storages were filled with a gravel-water mixture as storage material. Heat is fed into and out of the storage directly or indirectly. Based on the satisfactory results of the first 1,000 m^3 pilot plant which was built at ITW of Stuttgart University in 1984, the storage concept was applied for the construction of a 8,000 m^3 demonstration plant in the project Solaris in Chemnitz. The storage was completed in 1996, however the heating plant was not ready for operation before 540 m^2 of solar collectors (vacuum tubes) have been installed in 1999.

Another 1,500 m^3 storage was constructed with a modified concept for the solar assisted district heating system of the new housing project in Steinfurt-Borghorst. The storage is tightened with a doubled plastic liner. The space between the two layers is evacuated to allow a permanent control of the water-tightness during construction and operation. As heat insulation material expanded glass granules were used for seasonal storages for the first time.

The first German pit storage that is only filled with water is planned to be built in Eggenstein-Leopoldshafen in 2007. It will be the first pit storage with a self supporting roof.

Borehole thermal energy storage

In this kind of storage the heat is directly stored in the water-saturated soil. U-pipes – the so called ducts – are inserted into vertical boreholes to build a huge heat exchanger. While water is running in the U-pipes heat can be fed in or out of the ground. The heated ground volume comprises the volume of the storage. The upper surface of the storage is heat insulated.

Since 1997 a pilot borehole thermal energy storage is in realization in Neckarsulm. Due to the fact that the storage can only be heat insulated on top, heat losses might be quite high when the storage is heated noticeable above ground temperature. This matter is in observation in Neckarsulm because the maximum design temperature of the storage is 85 °C. Before the storage was built, at first the feasibility of the storage concept was proven with the installation of a 5,000 m^3 prototype storage at the site of the plant. The ducts are made of polybuthene and doubled in U-shape in every borehole with a depth of 30 m. The design data of the model calculations have been validated by the experimental results of the monitoring programme. In 1999, the storage was enlarged to a storage volume of 20,000 m^3. In 2002 the next phase of the solar assisted district heating project was started: The borehole storage was enlarged to 63,300 m^3 storage volume reaching half of the finally planned volume. The borehole thermal energy storage that is going to be built in 2007 in Crailsheim indicates the next generation of this kind of storages. The storage is explained in detail in the following.

Aquifer thermal energy storage

Naturally occurring self-contained layers of ground water – so called aquifers – are used for heat storage. Heat is fed into the storage via wells and fed out by reversing the flow direction. Aquifers can not be found everywhere. Thus an extensive exploration programme has to be passed for the building site before one can be sure that an aquifer thermal energy storage can be suitable.

Figure 8: Site plan of the solar assisted district heating system in Crailsheim, Germany

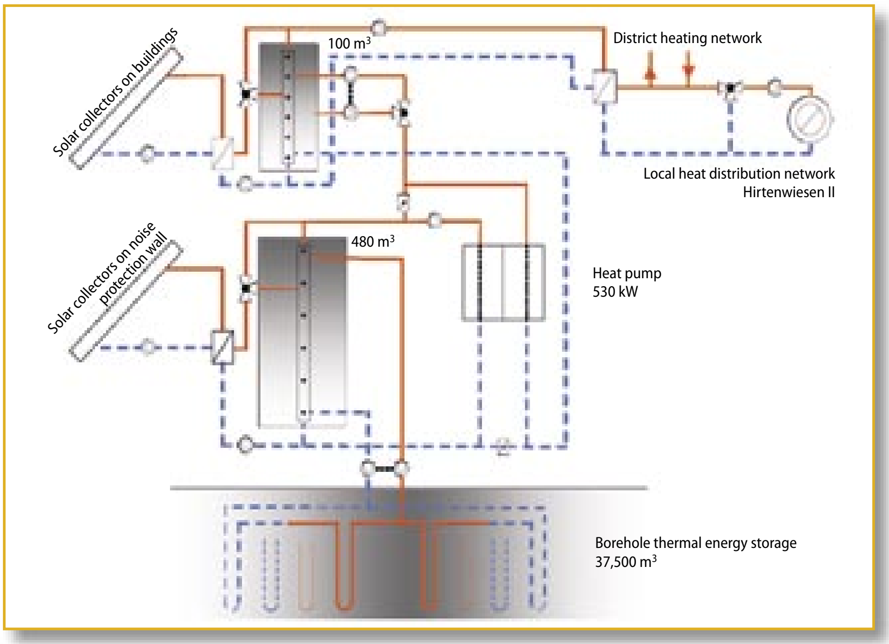


Figure 9: System concept of the solar assisted district heating system in Crailsheim, Germany

In the solar assisted district heating plant of the pilot project in Rostock-Brinckmanshöhe an aquifer is used as a low temperature seasonal storage. Due to the small size of the plant, the shallow 30 m deep aquifer has to be operated in a temperature range between 10 and 50 °C. The aquifer is charged with solar heat from a 1,000 m^2 solar collector roof. A maximal fraction of the stored solar heat can be recovered by a heat pump with 100 kW electrical power. In 2003 this pilot plant was the first of all plants that reached the strategic solar fraction of 50 % of the yearly heat demand. In the meantime more aquifer thermal energy storages have been built. These storages are not used to store solar thermal energy but to store waste heat of combined heat and power plants. Compared to the quite small storage in Rostock this storages are huge, e.g. like the aquifer thermal energy storage in Neubrandenburg, Germany.

Innovation project Crailsheim at a glance

In Crailsheim-Hirtenwiesen a former military area is recently transferred into a new residential area (see Figure 8). The smaller part of Hirtenwiesen 1 (left side in Figure 8) is covered with a couple of former military barracks buildings that are modernized and equipped with solar collectors on the roofs. The bigger area of Hirtenwiesen 2 will be covered mainly with smaller buildings (single family, row and twin houses). A school and a gymnasium have already been built and equipped with solar collectors (700 m^2). Hirtenwiesen 2 will be realized in two phases. Within the next years the first phase will be built. In a midterm future the second phase will be completed.

To the south, the whole area is separated from a commercial area by a noise protection wall. On this noise protection wall the main part of the solar collector area will be installed. Between the residential area and the noise protection wall a borehole thermal energy storage will be located that will be operated as a seasonal storage for solar thermal energy.

The solar system is separated into two parts: a diurnal and a seasonal part. The diurnal part consists of the solar collectors on the modernized buildings (Figure 11), the school and the gymnasium (Figure 10) and a 100 m^3 buffer tank (Figure 1) that is located close to the school. The solar energy from this part can mostly be used directly to supply the heat demand from the Hirtenwiesen 2 area.

The solar collectors on the noise protection wall (Figure 2) together with the BTES and a second water tank with 480 m^3 present the seasonal part of the system. The water tank of the seasonal part was added because of the high capacity rate of the solar collectors during summer. This high capacity rate can not be charged directly into the BTES during daytime but has to be distributed over a longer time period.

Heat from the seasonal part can be transferred to the diurnal part by a 300 m district heating pipeline either directly or via a heat pump. The heat pump allows a higher usability of the temperature difference of the seasonal heat storage and thus a higher storage capacity. In addition it reduces the temperature level in the storage and therefore results in lower storage heat losses. Furthermore the efficiency of the whole solar system becomes much more robust against high return temperatures from the heat distribution network.

An investigation of the ground parameters showed good prerequisites for a BTES. In the first 3 to 4 m below ground surface a noticeable natural ground water flow exists and has to be considered by the storage concept.

A feasibility study for the whole heat supply system showed the best economy (lowest solar heat cost) for the system concept displayed in Figure 9. According to the simulations the BTES will be heated up to 65 °C at the end of September, the lowest temperatures at the end of the heating period will be 20 °C. Maximum temperatures during charging will be above 90 °C.

The storage concept showed in Figure 12 was developed for the BTES to meet the mentioned boundary

Fig. 10: School with 500 m² of solar collectors

Fig. 11: Solar retrofitted and heat insulated apartment houses, converted from former military barracks buildings

Table 2: Data of the first phase of the solar assisted district heating system in Crailsheim with a borehole thermal energy storage (BTES)

Solar collector area	7,300 m²
Buffer storages (water tanks)	100 m³ (480 m³)
Seasonal thermal energy storage (BTES)	37,500 m³ ground volume
Service area	260 houses, school and gymnasium
Total heat demand	4,100 MWh
Heat pump	530 kW
Solar fraction	50 %*
Solar heat cost	0.19 €/kWha**
Recipient of subsidies / owner	Crailsheim City Utilities
Planner BTES	EWS GmbH, Lichtenau
System concept	ITW, University of Stuttgart and Solites
Technical developments	Solites and planners
Start of operation	June 2007

* TRNSYS-Simulations ITW
** according to calculation guideline of Solarthermie2000plus (*www.solarthermie2000plus.de*)

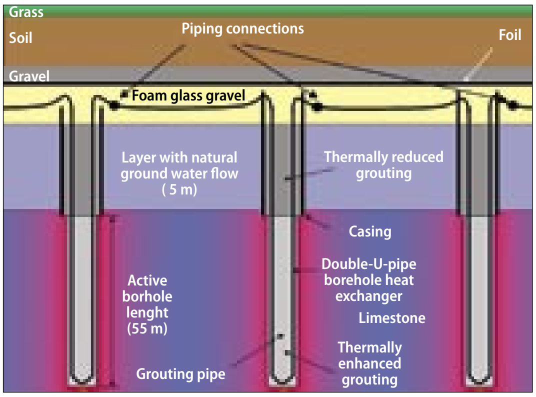


Figure 12: Vertical section of the borehole thermal energy storage in Crailsheim

conditions. The storage will contain 80 boreholes with a depth of 55 m. The storage volume will be a cylinder with the boreholes situated in a 3 m x 3 m square pattern. The ground heat exchangers will be double-U-pipes. Two different materials for the U-pipes were under discussion: a newly developed high-temperature polyethylene (PE-HT) or cross-linked polyethylene (PEX). Both materials have never been used for a high temperature storage application so far, although PEX has been used for cold and hot water distribution and for radiant heating systems for many years. A disadvantage of PEX is that connections can not be welded but have to be assembled by metallic press-fittings. The durability of this connection in wet ground conditions is discussed controversially. PE-HT on the other hand can be welded on-site but is a new material without any long-term experiences. In the end it came to the decision to use the PEX pipes.

The upper part (5 m) of the boreholes will be drilled with a bigger diameter than the lower part. After installation of the ground heat exchangers the lower part will be filled with a thermally enhanced grouting material (thermal conductivity 2.0 W/mK), while the upper part will be filled with a thermally reduced grouting material to reduce the heat transfer into this layer and thereby the thermal losses due to the ground water movement in this region. The horizontal piping on top of the storage will be embedded into an insulation layer of foam glass gravel. On top of the insulation layer a protecting foil (water-tight but open for vapour diffusion) and a drainage layer (gravel) will be installed below a 2 m layer of soil.

Prospects

In the upcoming years, further large-scale systems with seasonal heat storage will be built not only in Germany. Within the last years the interest on seasonal solar thermal energy storages internationally raised: The worlds largest central solar heating plant with over 19,000 m² of collector area, that is situated in Marstal, Denmark, was complemented with a seasonal pit heat storage of 10,000 m³ (*www.solarmarstal.dk*). In Canada the first seasonal solar thermal energy storage was built in 2006 in the residential area Drake Landing Solar Community in Okotoks as a borehole thermal energy storage (*www.dlsc.ca*).

Dirk Mangold

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