

The next Generations of Seasonal Thermal Energy Storage in Germany

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Abstract

Since 1996 eleven large scale solar thermal pilot plants with seasonal thermal energy storage have been realised within the federal R&D-programmes Solarthermie-2000 and Solarthermie2000plus. The storages accumulate solar thermal energy from summer to winter and enable high solar fractions of 40 to 50 % of the total annual heat demand of the connected residential areas. Results from the evaluation programme prove the technical feasibility and efficiency of the systems. Since 2007 three new plants were realized:

- The 5,700 m³ water tank in Munich was built of prefabricated concrete segments. The new heat insulation system was a result of a research project at the University of Stuttgart. The construction confirmed the expectations regarding a fast and cost-effective construction procedure and a high technical efficiency.
- In Crailsheim a borehole thermal energy storage (BTES) was built in 2008. There are 80 boreholes with a depth of 55 m, the storage volume is 37,500 m³ in a first construction phase.
- In Eggenstein a 4,500 m³ pit storage was finished end of 2007. Wells are used to charge and discharge heat by direct water exchange on top and at the bottom of the storage.

1. Introduction

Research on solar seasonal thermal energy storage (STES) in Europe 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) STES found their way to other European countries. The first research storages were built in Sweden, Denmark, the Netherlands, Switzerland, Italy, Greece and Germany. While most of these countries stopped their research programmes for STES, in 1993 Germany raised the long-term R&D-programme Solarthermie-2000 and the successor Solarthermie2000plus, which was implemented by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU). With support from these programmes eleven 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 currently largest plant is situated in Neckarsulm and comprises a collector area of 5,470 m² and a volume of the STES of 63,300 m³ ground volume.

Solar heat cost for the recent plants have been calculated to 24 €/ct/kWh for Munich, 19 €/ct/kWh for Crailsheim and 25 €/ct/kWh for Eggenstein (without VAT and subsidies). This means, for about twice the price of fossil fuel costs the CO₂-emission of entire urban areas can be reduced to 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 STES 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 to substantial cost reductions in storage technologies.

Table 1: Central solar heating plants with seasonal storage in Germany

	Hamburg ¹	Friedrichshafen ¹ final stage design (status 9,08)	Neckarsulm ¹ phase I (phase II)	Steinfurt ¹	Chemnitz ² phase I	Rostock ³	Hanover ⁴	Attenkirchen ⁵	Munich	Crailsheim phase I (status 9,08)	Eggenstein
start of operation	1996	1996	1997 (2001)	1998	2000 (aborted: 2006)	2000	2000	2002	2007	2007	2008
service area	124 RH	final stage: 570 apartments in MFH (390)	6 MFH, shopping centre, school, gym., home for elderly etc. (25 000)	42 apartments in 22 SFH and small MFH	design: office building, hotel and shopping centre 4 680	108 apartments in MFH	106 apartments in MFH	30 SFH	300 apartments in MFH	260 apartments in SFH, DH u. RH, school, gym.	school, sports centre, fire station
heated area	14 800	39 500 (33 000)	(25 000)	3 800	4 680	7 000	7 365	6 200	24 800	40 000	12 000 ⁶
solar collector area (aperture)	3 000 FP	5 600 FP (4 050)	2 700 FP (5 469)	510 FP	540 VTC	1 000 FP	1 350 FP	800 FP	2 900 FP	7 300 FP (5 050 FP)	1 600 FP
storage volume	4 500 TTES	12 000 TTES	100 TTES + 20 000 BTES (200 + 63 300)	1 500 PTES	8 000 PTES	30 TTES 20 000 ATES	2 750 TTES	500 TTES + 9 350 BTES	5 700 TTES	480 + 100 TTES + 37 500 BTES	4 500 PTES
total heat demand	1 610 MW _h / a	4 106 (3 000)	1 663 (2 200)	325	phase 1: 573	497	694	487	2 300	4 100	1 150
solar net energy* [§]	789	1 915	832	110	phase 1: 169	307	269	378	1 080 ⁵	2 050 ¹	430
solar fraction [§] *	49	47	50	34	phase 1: 30	62 ³	39	55 [#]	47 ⁵	50 ¹	37*
cost solar system [§]	2,2 million Euro	3,2	3,5	0,5	phase 1 + 2: 1,4	0,7	1,2	0,76	2,9	4,5	1,1 ⁶
solar heat cost [§] *	25,7 Ct./- kWh	15,9	26,5	42,3	phase 1 + 2: 24,0	25,5	41,4	19,0	24,0	19,0	25,0

*: calculated values for long-term operation, [#]: primary energy saving, [§] without VAT and subsidies, with planning
¹: data ITW University of Stuttgart, ²: data TU Chemnitz, ³: data Geothermie Neulandenburg, ⁴: data IGS University of Brunswick, ⁵: data ZAE Bayern, ⁶: data PKI
SFH: single family house, DH: detached house, RH: row house, MFH multifamily house
FP: flat plate solar collector, VTC: vacuum tube collector
TTES: tank thermal energy storage, PTES: pit thermal energy storage, BTES: borehole thermal energy storage, ATES: aquifer thermal energy storage

2. Central solar heating plant

Most of the existing pilot STES are integrated in central solar heating plants (Fig. 1). 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 space heating. In case STES is included in the plant, more than 50 % of the fossil fuel demand of an ordinary district heating plant can be replaced by solar energy. The storage is included in the plant to store solar thermal energy during summer and provide solar energy also through the heating period in winter.

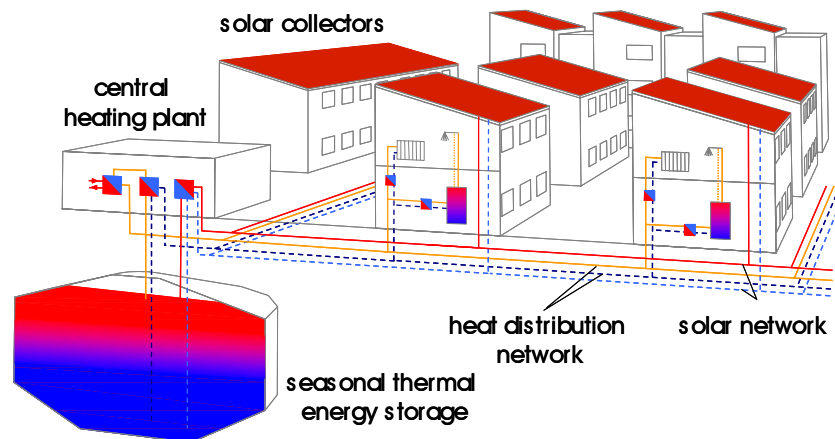


Fig. 1: Scheme of a central solar heating plant with seasonal storage.

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.

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 space heating and domestic hot water preparation by solar thermal energy, and solar systems with seasonal heat storage with solar fractions of about 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 close to the heating central. The heat obtained from the collectors is transported via a solar network to the heating central and is directly distributed to the buildings. The surplus heat of the summer period is fed into the STES. All over Germany the sun provides more than two third of its yearly energy supply only during the summer period. Thus during the space 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 space heating period, the STES 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.

3. Seasonal thermal energy storages

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 loses 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 held 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 of the storage: the amount of the energy, that is stored in the volume of the storage, loses 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. For this reason storing solar thermal energy seasonally with sensible heat starts to be energy efficient with large storage volumes of 1,000 m³ of water and more.

3.1 Storage concepts

During the past ten years of research on seasonal storage technologies four types of storages turned out as main focus for the ongoing engineering research. Fig. 2 gives an overview of these storage technologies. They are explained more detailed in the following sections. The decision for a certain type of storage mainly depends on the local prerequisites like the geological and hydro-geological 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 a specific project.

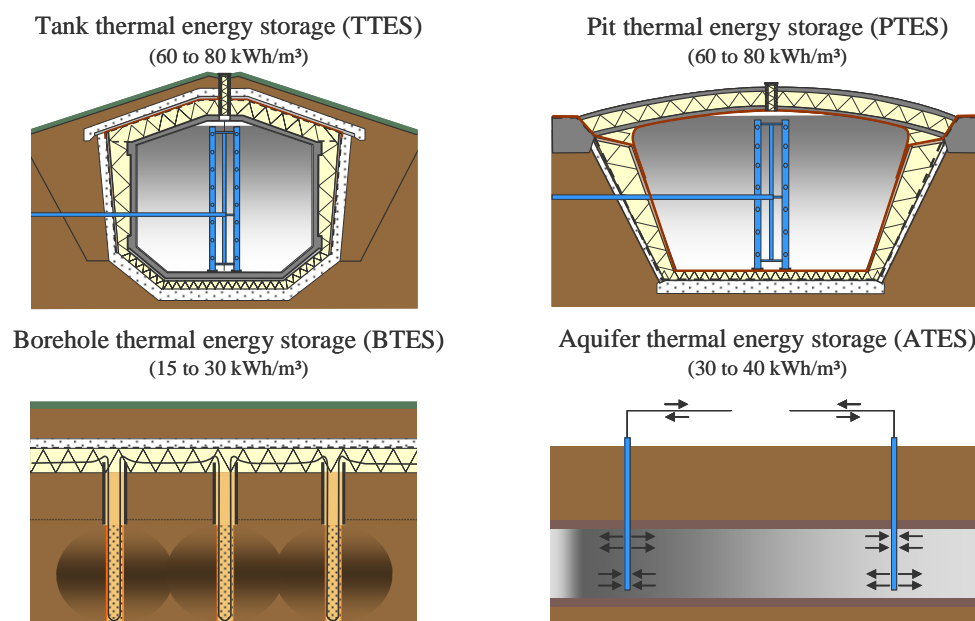


Fig. 2: Main concepts for seasonal thermal energy storage.

3.1.1 Tank thermal energy storage (TTES)

A TTES is built as a steel or reinforced and 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. These storages were built as reinforced and pre-stressed concrete tanks; they are heat insulated only on the roof and at the side walls and are lined with 1.2 mm stainless steel sheets. The cost analysis of these two storages showed that the stainless steel liners are quite expensive. With the storage in Hanover-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. In comparison to the first storages in Hamburg 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 storage in Munich goes one step forward in cost and energy efficiency. Fig. 3 gives a short sequence of the construction of the storage: The frustum at the bottom was built on-site while the side walls and the roof were built of prefabricated concrete elements that have a stainless steel liner at the inner surface. 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.



Fig. 3: Construction of the tank thermal energy storage in Munich, 2006.

The storage is heat insulated at the side walls and on top by expanded glass granules with a minimum thickness of 30 cm at the 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.

The specific investment cost of this storage construction is 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 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.

3.1.2 Pit thermal energy storage (PTES)

The usually naturally tilted walls of a pit are heat insulated and lined with a 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 (projects in Ottrupgard and Marstal) 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 have been – amongst others – investigated in a separate research project at the University of Stuttgart [1].

Due to the fact that the construction of the roof 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 by direct water exchange or indirectly via plastic pipes. Based on the satisfactory results of the first 1,000 m³ pilot plant which was built at ITW of Stuttgart University in 1984, the storage concept was applied for the construction of a 8,000 m³ 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 m² of solar collectors (vacuum tubes) have been installed in 1999.

Another 1,500 m³ storage was constructed with a modified concept for the solar assisted district heating system of a 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 most recent pit storage was built in Eggenstein in 2007, see Fig. 4.



Fig. 4: Construction of the pit thermal energy storage in Eggenstein, 2007.

3.1.3 Borehole thermal energy storage (BTES)

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

Since 1997 a pilot borehole thermal energy storage is in realisation in Neckarsulm. In a first step the feasibility of the storage concept was proven with the installation of a 5,000 m³ research storage at the site of the plant. The ducts are double-U-pipes made of polybutene 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 m³. In 2002 the next phase of the solar assisted district heating project was started: the borehole storage was enlarged to 63,300 m³ storage volume reaching half of the finally planned volume.

A next generation borehole thermal energy storage was built in Crailsheim in 2008. The storage consists of 80 boreholes with a depth of 55 m in a first construction phase. The storage volume (37,500 m³) is a cylinder with the boreholes situated in a 3 x 3 m square pattern, see Fig. 5. The ground heat exchangers are double-U-pipes made from cross-linked polyethylene (PEX). The storage volume will be doubled when the second part of the connected residential area is going to be built in some years.

The hydro-geological investigation showed an intermittent water movement in the upper part (5 m) of the storage volume. For this reason the boreholes were drilled with a bigger diameter in this part. After installation of the ground heat exchangers the lower part was filled with a thermally enhanced grouting

material (thermal conductivity 2.0 W/mK), whereas the upper part was filled with a thermally reduced grouting material to reduce the heat transfer into this layer and thereby the thermal losses due to the water movement in this region. The horizontal piping on top of the storage is 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) are installed below a 2 m layer of soil.

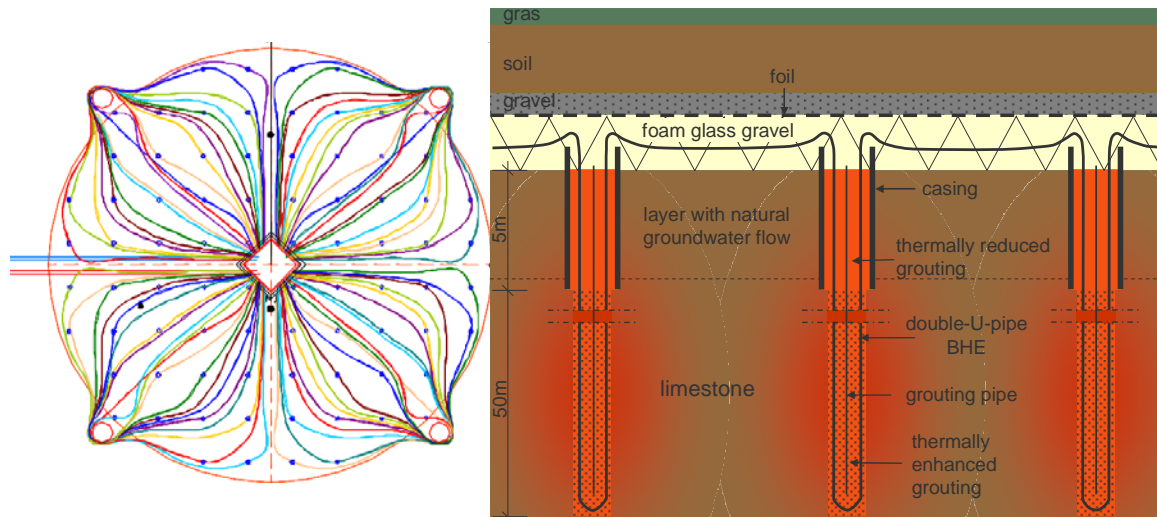


Fig. 5: Top view with horizontal piping (left) and vertical cross-section (right) of BTES in Crailsheim, 2008.

3.1.4 Aquifer thermal energy storage (ATES)

Naturally occurring self-contained layers of ground water – so called aquifers - are also used for thermal energy 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 ATES can be suitable.

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 m² solar collector roof. A maximal fraction of the stored solar heat can be recovered by a heat pump with 100 kW thermal 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.

3.2 Storage costs

Fig. 6 presents the cost data of the built pilot and demonstration storages of Table 1 and some 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. 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 system, 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.

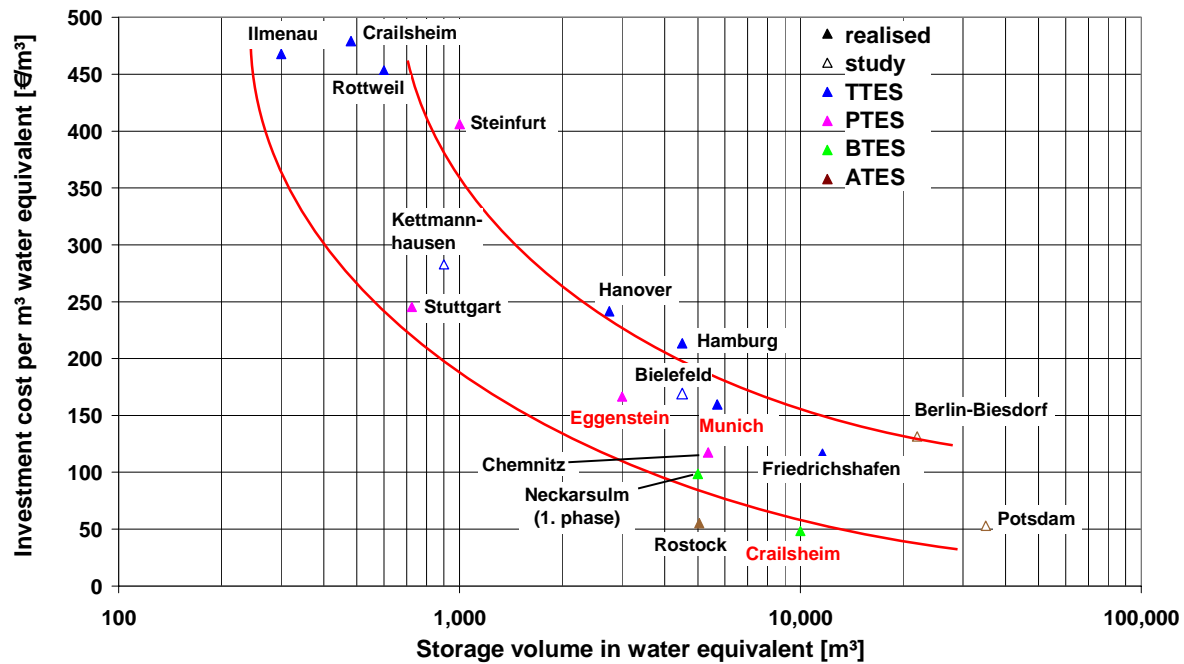


Fig. 6: Specific investment cost for STES (without VAT; red: new plants)

4. Conclusion

In the upcoming years further large-scale systems with STES will be built world-wide. Within the last years the interest on seasonal solar thermal energy storages internationally raised: the worlds largest central solar heating plant with 19,000 m² of solar collector area is situated in Marstal, Denmark and 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 BTES (www.dlsc.ca).

Ongoing R&D will focus on improving the cost-effectiveness of the storage technologies by a further reduction of the specific storage construction costs and by increasing the technical efficiency and durability and by this the useable heat output of the storage. More cost effective storage technologies are considered for the implementation in different applications like combined solar and biomass systems.

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References

- [1] F. Ochs, (2007). Weiterentwicklung der Erdbecken-Wärmespeichertechnologie (Development of Pit Thermal Energy Storage Technology, in German), Report, Institute for Thermodynamics and Thermal Engineering (ITW), University of Stuttgart, Germany