SEASONAL THERMAL ENERGY STORAGE IN GERMANY

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Abstract – The paper presents a comprehensive overview and review of the present status of research, development and demonstration of seasonal thermal energy storage in Germany. Since 1993 the activities are funded by several federal Ministries in the R&D-programme "Solarthermie-2000". One aim of "Solarthermie-2000" is to improve and demonstrate the technical and economic feasibility of different seasonal thermal energy storage concepts and technologies. The most promising storage concepts are investigated including: hot-water heat stores with and without liners, gravel-water, duct and aquifer heat stores. The programme comprises basic R&D on storage concepts, design, construction, long term monitoring and evaluation of so far eight large scale demonstration plants. The demonstration plants are designed to cover between 35 and 60 % of the annual heat demand of new housing areas by solar energy. The first plants of the programme are in operation since 1996. The data and experiences show that all investigated storage concepts are working without major technical problems. The annual heat output of the stores strongly depends on the return temperature of the connected district heating net which is determined by the heating systems of the connected consumers. Obviously a low temperature heating system in buildings is necessary to optimise the thermal output of the seasonal heat storage systems.

1. INTRODUCTION

The technology of seasonal heat storage is investigated in Europe since the middle of the 70´s. First demonstration plants were realised in Sweden in 1978/79 (Dalenbäck 1988, Lundin 1985) based on results of a national research programme. Within the IEA (International Energy Agency), “Solar Heating and Cooling” programme, experiences where worked out and exchanged in Task VII “Central Solar Heating Plants with Seasonal Storage (CSHPSS)” since 1979.

The first German programmes focused on basic research including model calculations, laboratory experiments and the construction of small scale pilot plants. The technical and economic feasibility of the storage concepts had to be proven. As a result of these investigations the first seasonal heat store in Germany was built in 1985 at the University of Stuttgart as a gravel-water heat store (Hahne, 2000). Following this, high priority has been given to R&D on large scale seasonal thermal energy storage in central solar heating plants within the governmental programme “Solarthermie-2000” since 1993, see figure 1. Large collector areas deliver solar heat to a central heating plant via a solar net. Surplus heat in summer is charged into the seasonal heat store which is also connected to the heating plant. In autumn and winter the stored solar heat supports the heat supply of the district heating system.

Since 1996 eight CSHPSS demonstration plants have been built in Germany within “Solarthermie-2000”. They are designed for solar fractions of between 35 and 60% of the total annual heat demand for domestic hot water preparation and space heating of the connected residential areas (Schmidt et. al., 2001; Mangold et. al., 2003). Several technologies for seasonal heat storage have been further developed and tested within these projects.

In the following paragraphs the present status of R&D for seasonal heat storage concepts in Germany is summarized.

2. TECHNOLOGIES FOR SEASONAL THERMAL ENERGY STORAGE

Based on the results of former R&D-work, four main types of seasonal heat stores have been used in the German demonstration plants in the last years (see figure 2). Hot-water and gravel-water heat stores have a strictly separated storage volume consisting of water or a mixture of gravel (or sand / soil) and water. They have a heat insulation to reduce heat losses to the surroundings at least on top and at the side walls. Duct and aquifer heat stores do not have an artificial container construction but use the more or less undisturbed ground for heat storage. In case of a duct heat store the heat exchange with the ground is realised with vertical heat exchangers. With aquifer heat stores direct groundwater exchange is used. The four storage concepts are discussed in detail in the following sections.

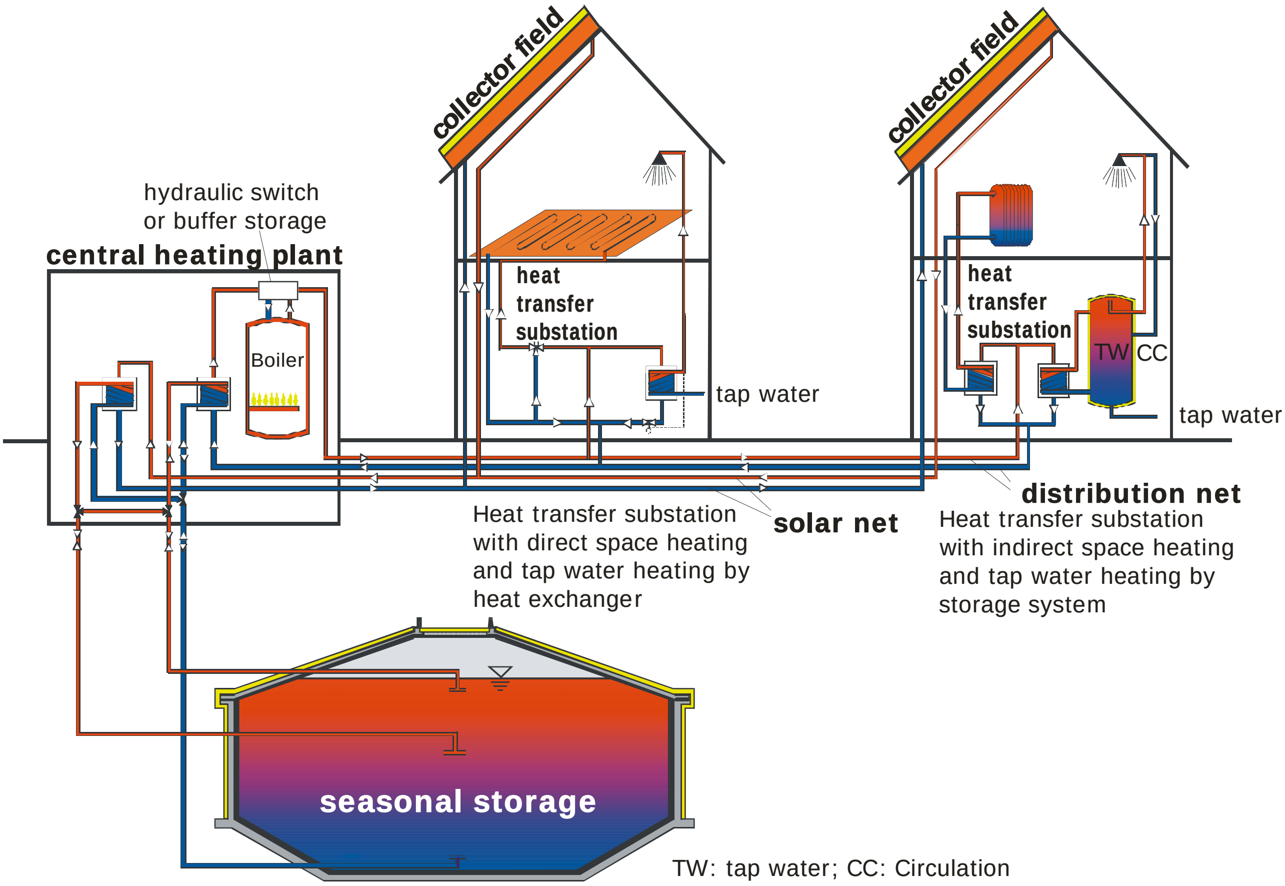

Figure 1: Central solar heating plant with seasonal storage (CSHPSS)

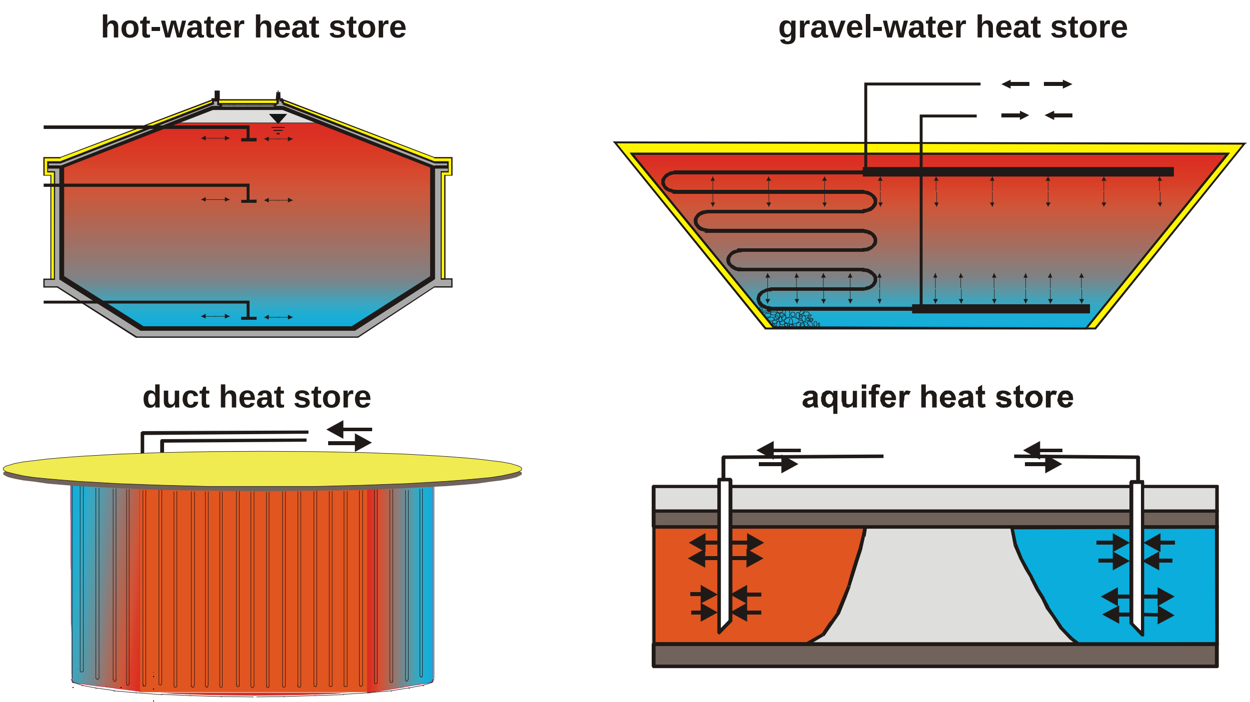

Figure 2: Technologies for seasonal thermal energy storage

Table 1 gives a summary about realised seasonal heat stores in Germany.

Table 1: Seasonal heat stores in Germany

location	type	size [m³]	start of operation
Rottweil[1)]	hot-water (concrete)	600	1995
Friedrichs-hafen	hot-water (concrete)	12 000	1996
Hamburg	hot-water (concrete)	4 500	1996
Ilmenau[1)]	hot-water (GFP)	300	1997 / 98
Hannover	hot-water (HDC)	2 750	2000
Stuttgart[2)]	gravel-water	1 050	1985
Chemnitz	gravel-water	8 000	1995 / 2000
Augsburg[2)]	gravel-water	6 500	1997
Steinfurt	gravel-water	1 500	1999
Neckarsulm	duct	63 360	1997 / 98 / 2001
Berlin[2)]	aquifer	-	1999
Rostock	aquifer	20 000	2000
Attenkirchen	hot-water / duct	9 850	2002

GFP: glass fibre reinforced plastics; HDC: high density concrete
[1)]: pilot store, not seasonal; [2)]: not within "Solarthermie-2000"

Hot-water heat store

So far seasonal hot-water heat stores usually have a tank construction built of reinforced concrete. The storage material is water, which gives good values concerning specific heat capacity and possible power-rates for charging and discharging.

The first heat stores (Rottweil, Friedrichshafen and Hamburg) have been built with an additional inner stainless-steel liner to guarantee water tightness, to protect the heat insulation on the outside and to reduce heat losses caused by steam diffusion through the concrete wall. With the development of a new high density concrete (HDC) material it was possible to built the store in Hannover without an inner steel-liner. Figure 3 shows cross-sections of the stores in Friedrichshafen and Hannover and the affiliated wall constructions.

The older stores have been built with only two levels for charging and discharging (on top and at the bottom). The Hannover store has a third device which is located below the upper third of the storage volume. This provides the following advantages during operation: it enables an optimised stratification in the store because low temperature heat can be charged into the store without disturbing higher temperature layers on top of the store. In addition simultaneous charging and discharging of the store at different temperature levels becomes possible.

For the heat insulation a granulated foam glass has been used in Hannover, which is filled into textile bags at the side walls. The advantage of this material compared to the former used mineral wool is a faster and easier installation procedure and a better drying performance if it becomes wet. In Hannover, the insulation layer is protected by a steam barrier because the HDC is not absolutely tight against steam diffusion, see figure 3.

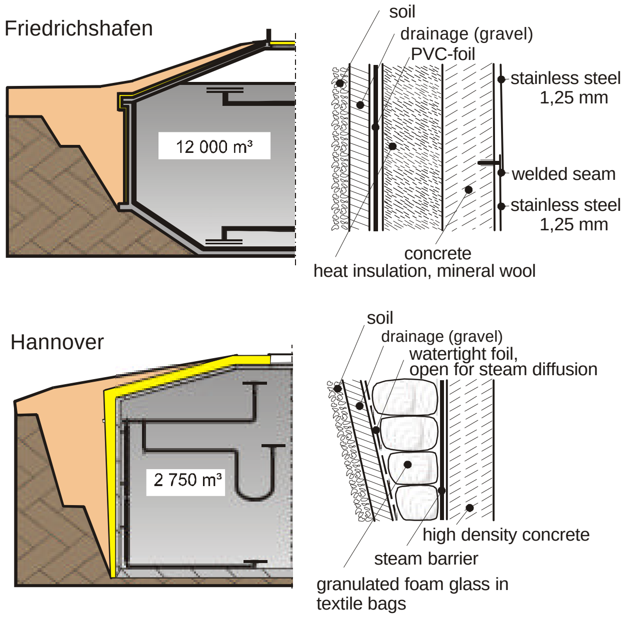

Figure 3: Construction of the hot-water heat stores in Friedrichshafen and Hannover

For some years glass fibre reinforced plastics (GFP) are studied as a new wall material at the Technical University of Ilmenau. The compound wall construction consists of two layers of GFP and an inner insulation layer. The tank is built of modules that are connected together on-site. Pilot stores with volumes of 20 and 300 m³ have been built by now.

Gravel-water heat store

To avoid an expensive tank construction, gravel-water heat stores only have a plastic liner separating the storage material and the surrounding soil, see figure 4. The storage material usually is a mixture of gravel and water, also sand/water or soil/water mixtures are possible. Because of the reduced specific heat capacity, the volume of the store has to be approximately 50% bigger compared to a hot-water heat store to store the same amount of heat at the same temperature levels.

Charging and discharging can either take place by direct water exchange or via plastic pipes, as shown in figure 4. Stratification should be supported by the charging devices. Side walls and the top are normally heat insulated. Depending on the size and shape bottom insulation can be advisable as well. Because of the liner materials, operating temperatures are limited to approximately 90 °C.

The wall construction of the currently newest store in Steinfurt consists of a protection fleece at the inside, a double poly-propylene (PP) lining with a vacuum control system to identify leakages during installation and operation, a steam barrier, heat insulation (granulated foam glass) and a drainage system.

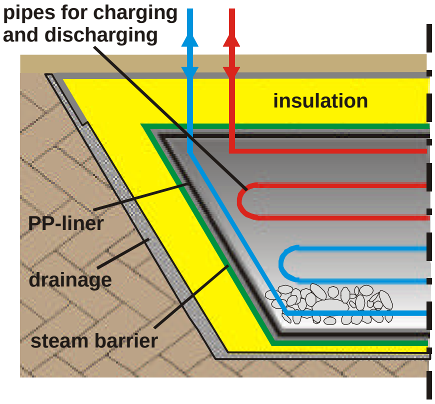

Figure 4: Construction of the gravel-water heat store in Steinfurt

Duct heat store

Duct heat stores do not have an exactly separated storage volume. The ground is used directly as the storage material in this case. To be able to charge heat into the ground a number of vertical borehole heat exchangers (BHE) are installed into a depth of normally 30 to 100 m. BHEs can be single- or double-U-pipes or concentric pipes mostly made of synthetic materials, see figure 5. In Germany, double-U-pipes made of poly-butylene (PB) are used for heat storage application because of the high upper temperature limit of 90 °C. The space between the pipes and the borehole wall is usually refilled with a grouting to reduce the thermal borehole resistance. If the borehole is stable enough also water can be refilled.

Distances between boreholes vary between 1.5 and 3 m, depending on size and depth of the store. Heat insulation can only be installed on top.

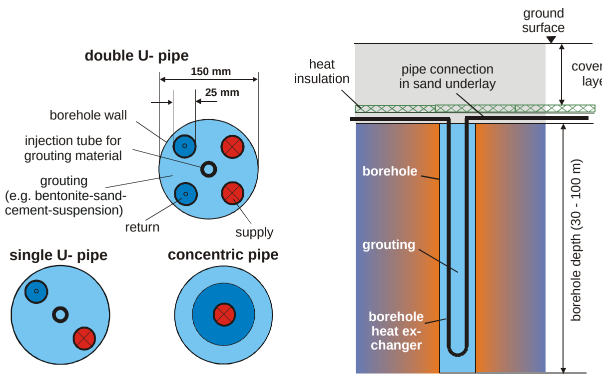

Figure 5: Types of borehole heat exchangers and sample installation

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

For duct heat stores, water-saturated clay and claystones as well as rock are suitable ground conditions because of the high heat capacity. Simultaneously they are tight enough to prevent considerable ground water flow.

The advantages of duct heat stores are the extendability and the lower effort for construction compared to hot-water and gravel-water heat sores. This also leads to lower costs. On the other hand the size of a duct heat store has to be three to five times higher compared to a hot-water heat store for the storage of the same amount of heat. This is because of the reduced heat capacity of the storage material and the smaller power rates for charging and discharging due to the heat transfer in the BHEs. Often an additional buffer store is necessary as well.

Figure 6 shows a horizontal cross section of the duct heat store in Neckarsulm. The store has been built in three phases of construction by now (2. stage of expansion). The remaining part for the final stage will be added as soon as the supplied residential area has reached the required heat demand.

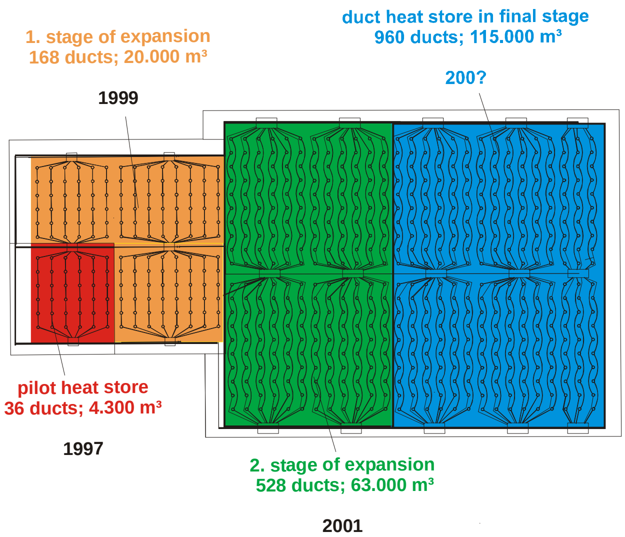

Figure 6: Duct heat store in Neckarsulm

Aquifer heat store

Aquifers can be distinguished in water saturated porous aquifers in sand, gravel or eskers and fractured aquifers in limestone, sandstone, igneous or metamorphic rock (Sanner, 1999). For the usage as a heat store the hydraulic conductivity has to be high ($> 1{\cdot}10^{-5}$) and no natural groundwater flow should be existent. With impervious layers above and below the aquifer layer it can be used for heat storage by drilling two wells (or groups of wells) and using the groundwater as the heat carrier fluid, see figure 7. During charging periods cold groundwater is extracted from the cold well, heated up by the heat exchanger and injected into the hot well. In discharging-periods the flow direction is reversed. Because of the different flow directions both wells have to be equipped with pumps, production- and injection-pipes.

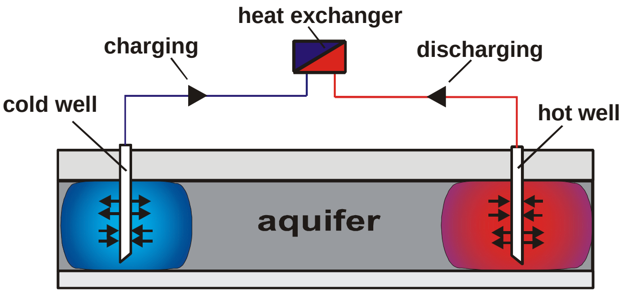

Figure 7: Scheme of an aquifer heat store

No heat insulation is possible for this kind of store. To keep heat losses in an acceptable range for high temperature application, the surface-volume-ratio has to be low. This applies for large storage volumes with more than 100 000 m³. Also, especially for high temperature heat storage, a good knowledge of the mineralogy, geochemistry and microbiology in the underground is necessary to prevent damage to the system caused by well-clogging, scaling etc..

In Germany, two aquifer heat stores are in operation in Rostock and in Berlin. The Berlin plant supplies the German parliament buildings including the “Reichstag”. Strictly speaking it consists of two separated stores: a cold store in a depth of about 60 m and a heat store in a depth below 300 m (Sanner, 1999).

Summary

A summary of the main parameters of the different concepts for seasonal heat storage is shown in table 2. For all concepts a geological investigation has to be made in the pre-design phase. The highest demands with regard to this are made by duct and aquifer heat stores.

The legal requirements have to be checked in the pre-design phase as well. In most countries the usage of the ground for heat storage has to be approved by the local water authorities to make sure that no interests regarding drinking water are affected. This can also become necessary if the ground surrounding a storage tank is heated up by heat losses.

For the choice of a suitable storage concept for a specific plant all relevant boundary conditions have to be taken into account: local geological situation, system integration, required size of the store, temperature levels, power rates, legal restrictions etc.. Finally, decisions should be based on an economic optimisation of the different possibilities.

After construction the stores have start-up times between three and five years, depending on the storage concept, to reach normal operating conditions. Within this time, the surrounding ground is heated up and the heat losses of the store are higher than during long-term operation.

3. ECONOMICS

The composition of the investment costs is presented for each storage concept exemplarily in figure 8. The main costs of the hot-water heat store in Friedrichshafen were caused by the concrete construction (36%). Also ground works and steel-liner are responsible for considerable parts of the costs (23% each). For the gravel-water heat store in Steinfurt, the sealing of the pit by the double-PP-lining was the most expensive part (32%) followed by the insulation (25%) and the ground works (21%). The costs for the gravel (14%) depend on the availability at the specific site and the additional effort for cleaning.

Table 2: Comparison of storage concepts

hot-water	**gravel-water**	**duct**	**aquifer**
storage medium			
water	gravel-water	ground material (soil / rock)	ground material (sand/gravel…-water)
heat capacity in kWh/m³			
60 - 80	30 - 50	15 - 30	30 - 40
storage volume for 1 m³ water equivalent			
1 m³	1.3 - 2 m³	3 - 5 m³	2 - 3 m³
geological requirements			
• stable ground conditions • preferably no groundwater • 5 - 15 m deep	• stable ground conditions • preferably no groundwater • 5 - 15 m deep	• drillable ground • groundwater favourable • high heat capacity • high thermal conductivity • low hydraulic conductivity ($k_f<1 \cdot 10^{-10}$ m/s) • natural ground-water flow < 1 m/a • 30 - 100 m deep	• natural aquifer layer with high hydraulic conductivity ($k_f>1 \cdot 10^{-5}$ m/s) • confining layers on top and below • no or low natural groundwater flow • suitable water chemistry at high temperatures • aquifer thickness 20 - 50 m

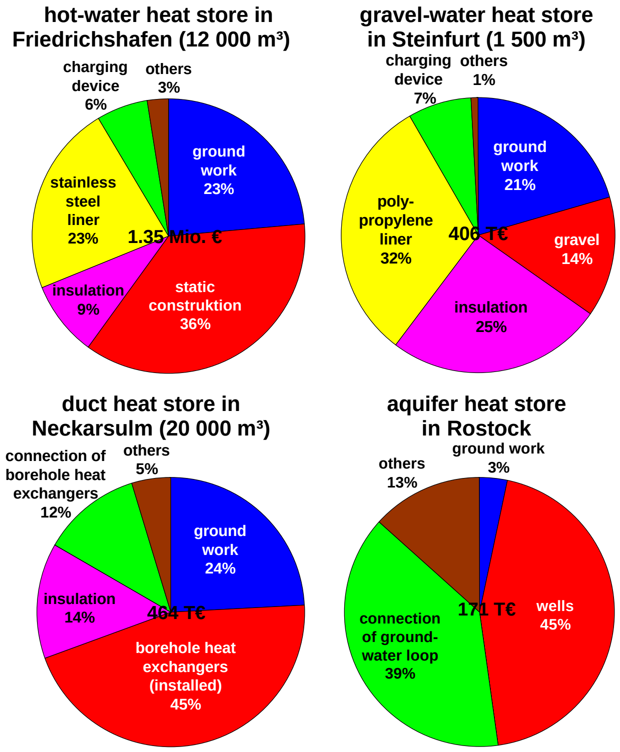

Figure 8: Composition of investment costs (including design, without VAT)

The installation work for the borehole heat exchangers including material and drilling works caused almost half of the costs (45%) of the Neckarsulm duct heat store. The additional ground works (24%) cover the excavation and refilling of three meters of ground on top of the store. In Rostock the construction of the two wells (45%) and the connection to the central heating plant (39%) were the predominant parts of the costs for the aquifer heat store.

Figure 9 shows the investment costs of several realised projects and studies referred to the storage volume in water equivalent. The water equivalent is the corresponding water volume to store the same amount of heat. Appropriate sizes for seasonal heat storage are located between 2 000 and 20 000 m³ water equivalent. Within this range the investment costs vary between 40 and 250 Euro/m³. Generally, hot-water heat stores are the most expensive ones. On the other hand, they have some advantages concerning the thermodynamical behaviour and they can be built almost everywhere. The lowest costs can be reached with aquifer and duct heat stores. However, they often need additional equipment for operation like e.g. buffer stores or water treatment and they have the highest requirements on the local ground conditions.

The heat cost per kWh of stored heat can not be given in general because it depends very much on the application or the connected system. For the above mentioned central solar heating plants with seasonal heat storage the solar heat costs for solar fractions of around 50% are between 0.16 and 0.40 Euro/kWh (without subsidies). This represents the investment required to save 1 kWh of end energy use and is calculated according to VDI 2067

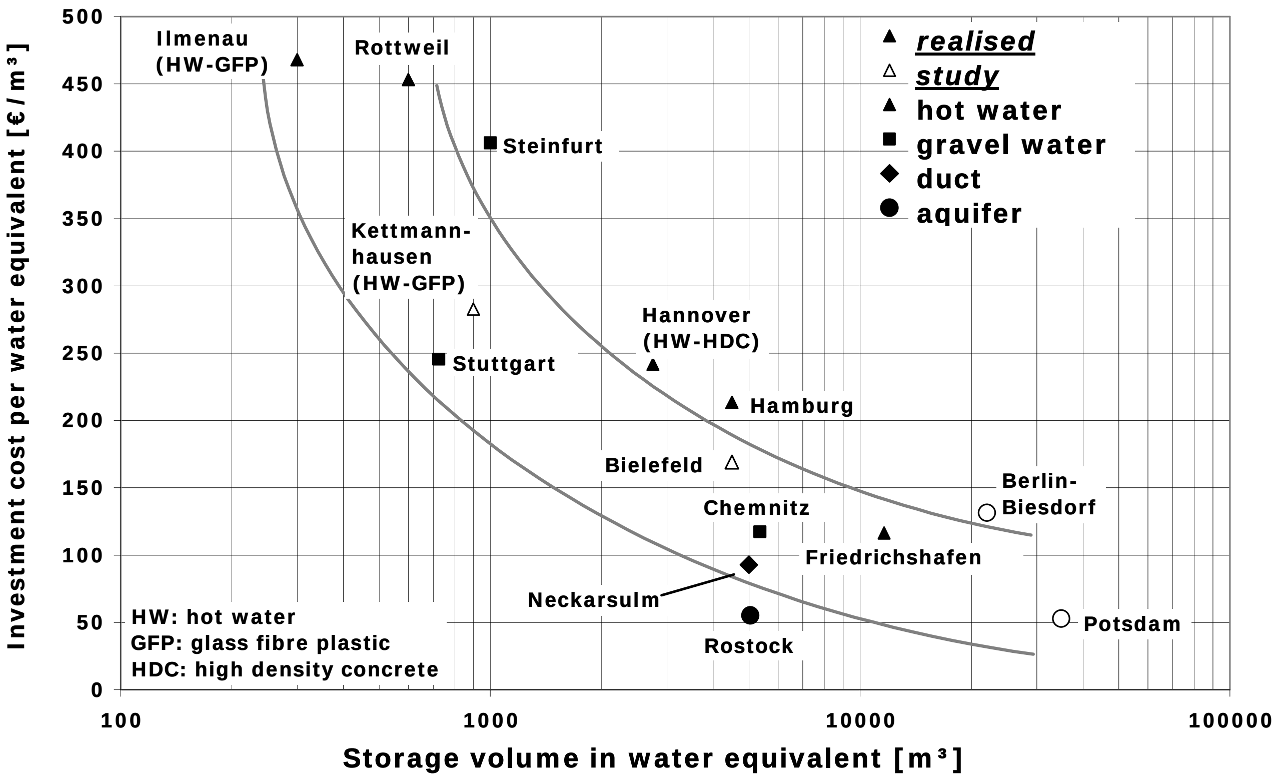

Figure 9: Investment costs of seasonal heat stores (including design, without VAT)

(VDI 2067, 1983). The figures are valid for the German market (calculation basis: market prices of 1997/98, without VAT, interest rate: 6 %). These costs can not compete with the costs of conventional district heating systems or decentralised systems, which have heat costs around 0.4 Euro/kWh, so far. Aim of the Solarthermie-2000 programme is to direct these systems into profitability in the future.

Other fields of usage, especially cooling and combined heating and cooling applications, can already compete on the market due to high costs for cold. Also applications like storage of waste heat or operational optimization of power plants with large scale heat storage can be competitive.

4. SUMMARY AND OUTLOOK

Seasonal heat storage is under investigation in Germany since the middle of the 70´s. Since 1996, eight demonstration plants for solar assisted district heating with seasonal heat storage have been built. Four concepts for seasonal heat storage have been further developed and evaluated in the course of these projects. The technical feasibility of the technology was proved – so far no serious malfunctions or breakdowns were observed.

Efficiency of the stores was less than predicted in the first projects. This was mainly caused by optimistic boundary conditions presupposed in the pre-design phase. Especially the return temperatures from the district heating net turned out to be the crucial point: high return temperatures reduce the effective heat capacity of the store because they provide the temperature limit for discharging. A heat store that is designed to operate between temperatures of 40 to 90 °C loses 20% of its heat capacity if it can only be discharged down to 50 °C because of high return temperatures! In newer plants more attention was paid to the complete system design including the heat distribution systems in the connected buildings to optimize the interaction between the components.

Profitability nowadays can not be reached in combination with solar assisted district heating systems. However, aim for the near future are heat costs that are at maximum twice the costs of conventional heating systems. Due to possible cost reductions, improved storage and system efficiencies and, on the other hand, rising costs for fossil fuels this seems reasonable.

Future work will focus on improvement of the cost-efficiency of the storage concepts. An ongoing R&D project deals with water-filled pit heat stores that only have a plastic sealing similar to the gravel-water heat stores instead of a static construction. This is a promising concept for a considerable cost reduction for hot-water heat stores.

Furthermore an extended field of possible applications will be investigated including cold storage, combined heat and cold storage, combined solar and biomass heat storage, operational optimization of cogeneration plants with large scale heat storage etc..

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