MONITORING RESULTS FROM GERMAN CENTRAL SOLAR HEATING PLANTS WITH SEASONAL THERMAL ENERGY STORAGE

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ABSTRACT

Central solar heating plants combined with seasonal heat storage enable high solar fractions of 50% and more. Several pilot central solar heating plants with seasonal heat storage (CSHPSS) built in Germany since 1996 have proven the appropriate operation of these systems and confirmed the high solar fractions. Four different types of seasonal thermal energy stores have been developed, tested and monitored under realistic operating conditions: Hot-water Thermal Energy Store, Gravel-water Thermal Energy Store, Borehole Thermal Energy Store and Aquifer Thermal Energy Store. In this paper heat balances based on measurements are presented for four German CSHPSS. The different types of thermal energy stores and the affiliated central solar heating plants and district heating systems are described. Their operational characteristics are compared with measurements gained from the monitoring program. Long-term operational experiences such as the influence of network return temperatures are shown and discussed.

1. INTRODUCTION

Since 1996 several pilot central solar heating plants with seasonal heat storage (CSHPSS) were realised within the framework of the research and demonstration programs “Solarthermie 2000” and “Solarthermie2000plus”. The plants are investigated under realistic operating conditions and are scientifically accompanied and analysed. Central solar heating plants with seasonal heat storage are designed for solar fractions of approx. 50%. These systems usually supply more than 100 flats via a district heating network. The seasonal mismatch between high solar irradiance in summer and high heat demand in winter is balanced by seasonal heat storage. Heat gained from solar collectors is transported via the solar network to a central heating plant and distributed to the buildings in case of demand. Solar collectors are installed preferably on large roofs and the seasonal thermal energy store is built into the underground. If neither the solar collectors nor the seasonal thermal energy store can cover the heat demand of the district heating network, a conventional gas condensing boiler typically provides additional heat. The design of CSHPSS is described in detail by [1]. Four different store types for seasonal heat storage have been developed in Germany since 1984. The selection of a store type depends among others on the geological and hydro-geological situation in the ground at the respective construction site. A preliminary geological examination of the site is recommended especially for Aquifer and Borehole Thermal Energy Stores. If different store types are feasible, an economic optimisation via system simulations should be conducted by taking the construction costs of the different concepts into account.

2. FRIEDRICHSHAFEN

In Friedrichshafen, close to the Lake of Constance, a CSHPSS was put into operation in 1996. The seasonal thermal energy store is realised as Hot-water Thermal Energy Store (HTES) made of reinforced concrete with a water volume of 12 000 m³ (height: 20 m, diameter 32 m). In 2004 the solar coupled district heating network was extended by a second residential area. Additional collector fields and buildings were connected to the system. The first residential area consists of 280 flats in multi-family houses and a kindergarten. The heated area amounts to approximately 23 000 m². In the first residential area 2 700 m² of solar collectors are installed on the rooftops, divided into seven fields. In the second residential area around 110 flats mainly in terraced houses were built. Another 1 350 m² of solar collectors were integrated into the system, installed on the roofs of the second residential area. Two gas condensing boilers cover the heat demand of the district heating networks when no solar energy is available. In figure 1 the scheme of the CSHPSS is shown.

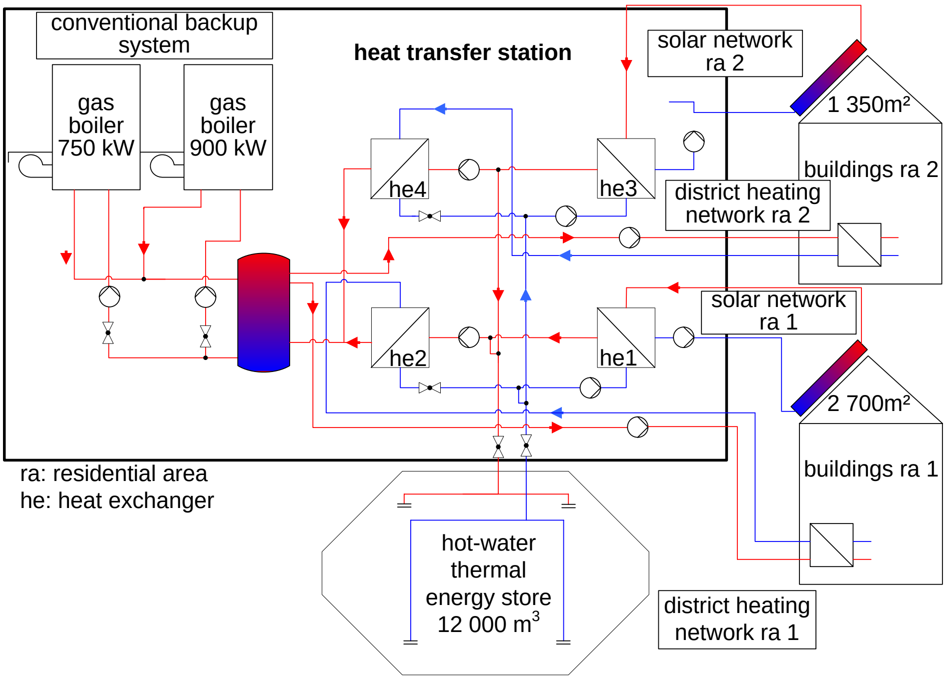

Figure 1: Scheme of the CSHPSS in Friedrichshafen

In table 1 the heat balances for the years 2003 to 2007 are shown. The solar fraction (based on total heat demand) varied between 24% and 33%. The design solar fraction related to the 1st residential area was calculated to 43%. This value has not yet been achieved for several reasons. The heat demand of the buildings is approximately 10% higher than expected. Furthermore, the design return temperature of the district heating network was supposed to be lower than 40°C (yearly average weighted by volume flow). In 2006 this value rose to 55.4°C. The measured heat losses of the thermal energy store, estimated to be 220 MWh/a, were between 386 MWh/a and 482 MWh/a, corresponding to a storage efficiency of approx. 60%. One of several reasons for the increased thermal losses is the HTES operation at higher temperatures than expected because of the high network return temperatures. Heat losses increase significantly since the lower third of the HTES is not thermally insulated.

In summary the operation of the CSHPSS in Friedrichshafen shows the functional efficiency of this pilot plant although the solar fraction and storage efficiency are lower and the network return temperature is higher than designed.

Table 1: Heat balances for the years 2003 to 2007 for the CSHPSS in Friedrichshafen

		2003	**2004**	**2005**	**2006**	**2007**
Solar yield of collectors	[MWh]	941[1)]	808[1)]	1179[2)]	1200[2)]	1400[2)]
per m² collector area	[kWh/m²]	348[1)]	299[1)]	291[2)]	296[2)]	346[2)]
Solar heat into district heating network	[MWh]	886[2]	743[2)]	764[2)]	803[2)]	962[2)]
per m² collector area	[kWh/m²]	-	-	189[2)]	198[2)]	238[2)]
Heat losses of the store	[MWh]	-	-	386	421	482
Overall heat delivery into the district heating network	[MWh]	3325[2)]	3013[2)]	3205[2)]	3017[2)]	2942[2)]
Heat losses of the district heating network of the 2nd residential area	[%]	7.7	8.8	-	7.3	5.1
Heat delivered by the gas boiler	[MWh]	2210	2270	2440	2310	1982
Solar fraction	[%]	27	25	24	26	33

[1)] Only residential area 1
[2)] Residential area 1 + 2

In figure 2 for the years 1997 to 2007 measured temperatures inside and around the HTES are depicted. The temperatures below the store have almost stabilised since 2005 but beside the store temperatures increase despite decreasing storage temperatures. The most likely reason is a moist thermal insulation which results in increased heat losses.

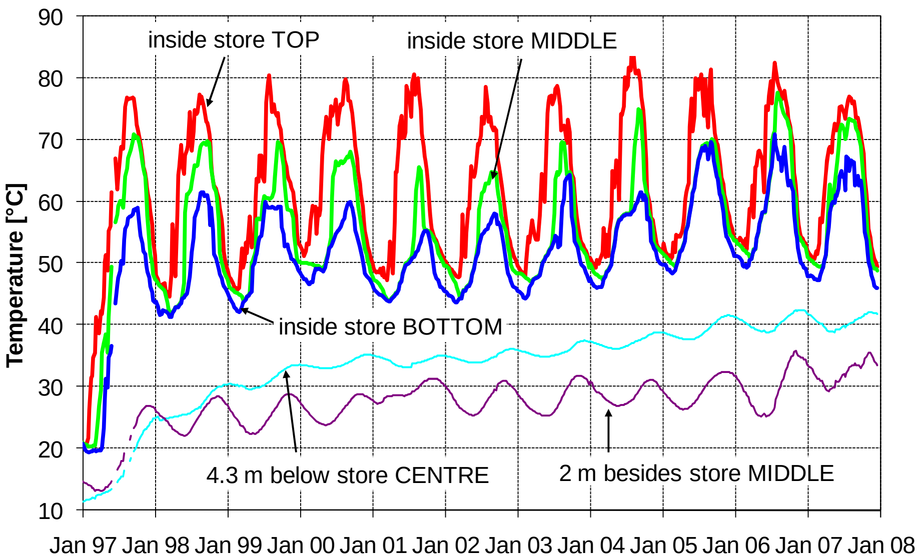

Figure 2: Measured temperatures inside and around the Hot-water Thermal Energy Store for the years 1997 to 2007

3. NECKARSULM

Since 1997 the first solar coupled district heating system with Borehole Thermal Energy Store (BTES) in Germany is being realised in Neckarsulm, located in the south-west of Germany. Presently about 300 flats, a school with gymnasium, a shopping centre and two residential homes for the elderly are connected to the district heating system. Solar thermal collectors with a total area of 5 670 m² respectively 3.97 MW_{th} are installed on different buildings, a carport and a noise barrier. The BTES which is used for seasonal heat storage was twice extended (1998 and 2001) and has now a volume of 63 360 m³ and 528 Borehole Heat Exchangers (BHE). The BHE are double-U-pipes and used to charge and discharge the BTES. In figure 3 the scheme of the solar coupled district heating system is shown. The BTES is directly connected to the district heating network and charged via two 100 m³ buffer stores by the solar collectors. The buffer stores are used for short-term heat storage to balance peaks in heat delivery from the solar collectors. The buildings are connected to the district heating system by a 3-pipe heat distribution network. The heat distribution network is supplied either by the buffer stores or the BTES, depending on the temperature level. A gas condensing boiler supplies additional heat if none of the stores is able to deliver heat at the requested temperature level. In order to increase the efficiency of the system an electrically driven heat pump with a power of 500 kW_{th} was integrated in 2008. Hydraulically, it is located between the two buffer stores. By use of the heat pump the BTES shall be discharged to lower temperatures which will decrease the heat losses and increases the heat capacity of the BTES.

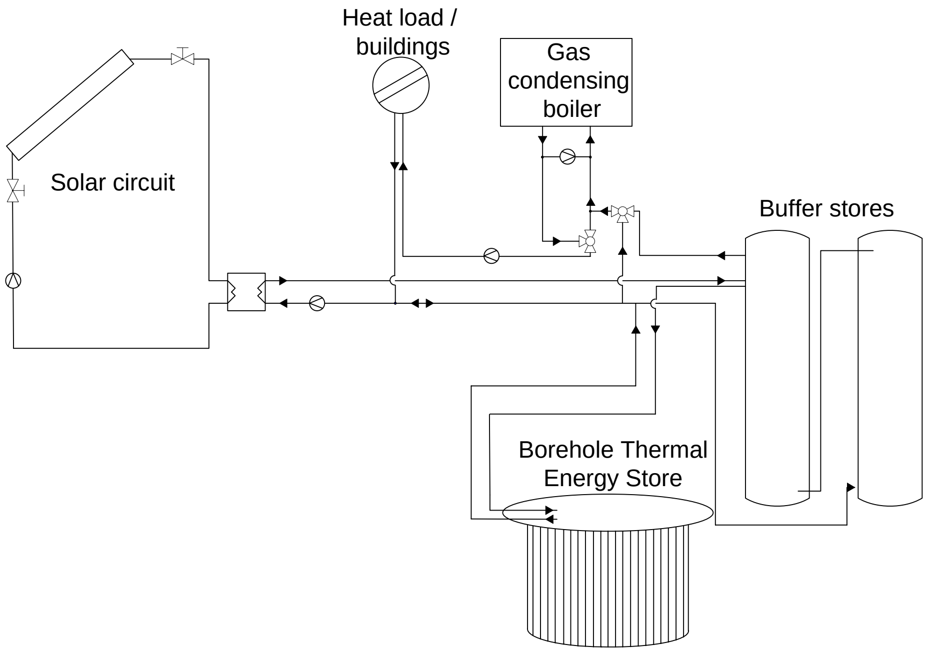

Figure 3: Scheme of the CSHPSS in Neckarsulm (without heat pump)

In table 2 the heat balances are shown for the years 2003 to 2007. Up to then the highest solar fraction (based on total heat demand) was achieved in 2007 (44.8%). The design solar fraction of 50% was not yet reached for several reasons. The collector area is about 10% smaller than designed and the network return temperatures are higher than expected, 47°C to 50°C instead of 40°C (yearly average weighted by volume flow).

Table 2: Heat balances for the years 2003 to 2007 for the CSHPSS Neckarsulm

		2003	**2004**	**2005**	**2006**	**2007**
Solar yield of collectors	[MWh]	2050[1)] 71[2)]	1629[1)] 38[2)]	1634	1805	1854
per m² collector area	[kWh/m²]	406[1)]	318[1),3)]	310.5	343	336
Solar heat into district heating network	[MWh]	700[1),2),4)]	755[1),2),4)]	1221	1011	1204
per m² collector area	[kWh/m²]	126[1)]	143[1)]	232	185	218
Overall heat delivery into the district heating network	[MWh]	1810 +81[5)]	2236[1)] +120[5)] 879[2)]	4825	2647	2807
Heat delivered by the gas boiler	[MWh]	1109	1481[1)] 879[2)]	3311	1510	1485
Solar fraction	[%]	39	34[1]	26.7	39.6	44.8

1) District heating system “Grenchenstraße” (CSHPSS with BTES)
2) District heating system “Eugen-Bolz-Straße” (adjacent district heating system)
3) 5007 m², collector field „Pflegeresidenz“ (256 m³) connected during the year
4) Heat losses of the solar network were subtracted. Only the solar heat delivery of the district heating system “Grenchenstraße” but not of “Eugen-Bolz-Straße” is included. For 2003 the heat losses of the solar network are not included within the calculation of the solar heat into the district heating system.
5) Heat losses of the solar network.

In figure 4 the temperatures in the centre of the 1st and 2nd extension of the BTES are shown for a depth of 10 m. Within the last years the maximum temperatures reached 65°C which is about 20 K less than the planned maximum temperatures. One reason amongst others is the smaller collector area than planned (6 300 m²). It can also be seen that in the first five years no heat was discharged since the BTES had to be heated up to a usable temperature level.

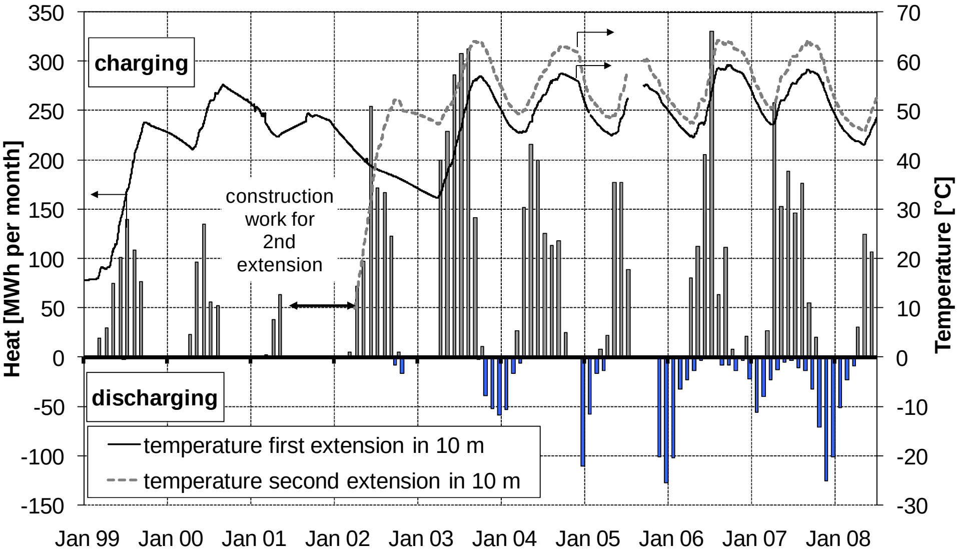

Figure 4: Measured heat quantities and temperatures in a depth of 10 m for the BTES Neckarsulm from 1999 to 2007

4. CRAILSHEIM

In Crailsheim the construction site "Hirtenwiesen" is arising from a former military compound. About 260 flats mainly in detached houses, a school and a gymnasium are to be supplied with thermal energy for space heating and hot water preparation via a district heating network. The expected heat demand will add up to 4 100 MWh/a, out of which 50% will be covered by solar energy. The solar heating plant consists of two parts, of which the first one was taken into operation in 2004. The first part consists of collector fields installed on apartment buildings, a school and a gymnasium (so far 1 558 m²), a hot-water buffer store with 100 m³ and a heat transfer station connecting the plant to the district heating network. The second, mainly seasonal operating part is currently under construction. It will consist of approximately 5 000 m² collector area mounted on a noise barrier, a second buffer store and a Borehole Thermal Energy Store. In figure 5 the functional principle of the CSHPSS in Crailsheim is depicted. All design data were obtained by transient simulations using the software package TRNSYS [5]. Further information on the solar heating plant is given in [2].

Table 3: Heat balances for the years 2006 and 2007 for the CSHPSS Crailsheim

		2006	2007
Solar yield of collectors	[MWh]	545	566
per m² collector area	[kWh/m²]	350	363
Solar heat into district heating network	[MWh]	473	507
per m² collector area	[kWh/m²]	303	326
Solar heat delivery into area Hirtenwiesen (I) and (II)	[MWh]	65 (I) 408 (II)	45 (I) 462 (II)
Overall heat delivery into the district heating network Hirtenwiesen II	[MWh]	2022	2255
Heat from a district heating network	[MWh]	1630	1765
Solar fraction	[%]	20	20

The heat balances (table 3) for the CSHPSS in Crailsheim, are given for the part with short-term heat storage. Furthermore the heat demand was about half of the design heat demand after the overall completion of the construction site.

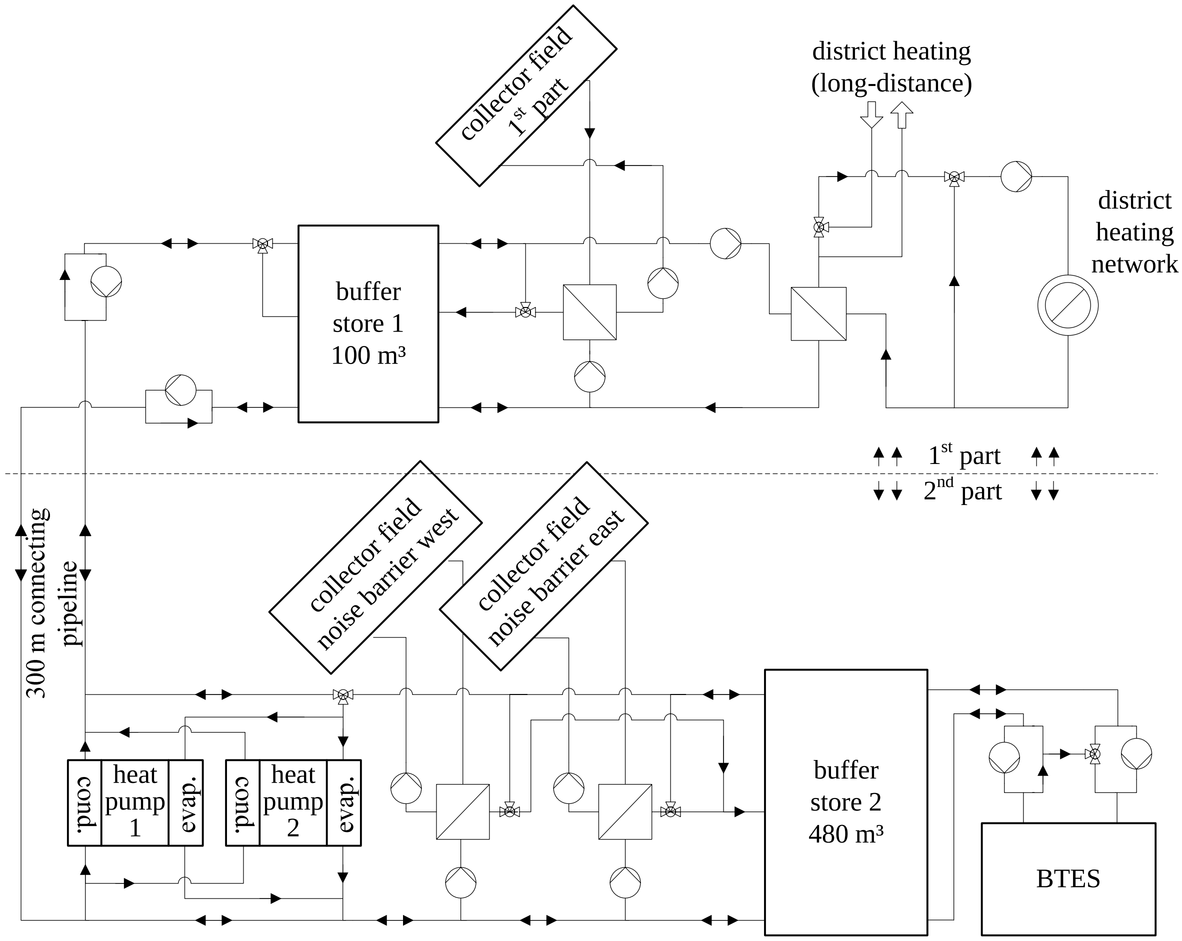

Figure 5: Scheme of the CSHPSS in Crailsheim

5. ROSTOCK

In May 2000 the first central solar heating plant with Aquifer Thermal Energy Store (ATES) was realised in Germany. The heating system supplies an apartment house with a total of 108 flats and a gross area of 7 000 m² with thermal energy for space heating and hot water preparation [3], [4]. The CSHPSS is designed in such a way that half of the heat demand for space heating and hot water preparation is covered by solar thermal energy. In 2005 a solar fraction of 57% was achieved. A collector area of 980 m² integrated in the roof of the building charges a 30 m³ buffer store (figure 6) with thermal energy. The heat is either used directly in the heat distribution network or the surplus is charged into the ATES located underneath the building. The ATES is equipped with two wells. The maximum temperature is limited to 50°C as higher temperatures may cause a change of the ground water composition. Due to the temperatures of 45/30°C of the heating network only a small amount of the heat stored in the ATES can be used directly at the beginning of the discharging season in autumn. A custom-made heat pump with a power of 110 kW_{th} is applied to discharge the ATES more effectively to temperatures of 10°C. The heat pump offers a temperature of 45°C at the condenser and a higher temperature of 65°C at superheated refrigerant position. Depending on demand these two temperature sources can directly be used for space heating or hot water preparation.

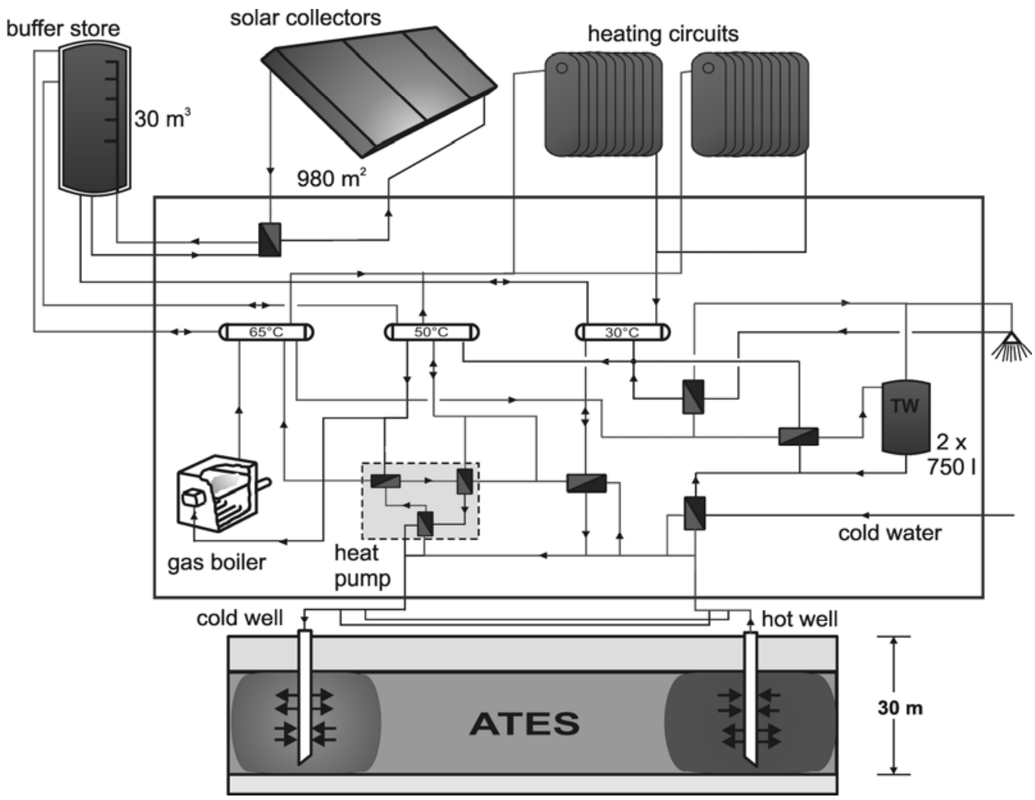

Figure 6: Scheme of the CSHPSS in Rostock

In table 4 the heat balances for the system in Rostock are presented for several years of operation. A defect of the heat pump in winter 2006/2007 caused a low solar fraction as the ATES could hardly be discharged during this period.

Table 4: Heat balances for the Rostock CSHPSS 2001-2007

		Planning	**2001**	**2002**	**2003** [1),2)]	**2005**	**2006**	**2007**
Solar yield of collectors	[MWh]	400	348	364	456	373	383	368
per m² collector area	[kWh/m²]	417	355	371	465	380	391	375
Heat charged into aquifer	[MWh]	234	214	245	295	205	230	214
Heat discharged out of aquifer	[MWh]	222	78	158	143	178	84	51
Solar heat supplied into network [3)]	[MWh]	306	211	278	304	346	238	204
per m² collector area	[kWh/m²]	319	216	283	310	353	242	208
Overall heat delivery into the district heating network inclusive network heat losses	[MWh]	538	656	644	623	605	596	571
Heat delivered by the gas boiler	[MWh]	61	420	322	279	210	333	351
Electric power consumption of heat pump	[MWh]	55	24	44	40	50	26	16
COP of heat pump	[-]	5	4.1	4.3	4.4	4.5	4.0	4.1
Solar fraction [4)]	[%]	62	32	43	49	57	40	36

1) The 2004 analysis was done by Thomas Schmidt (SWT, now Solites).
2) In 2003 temporary flow meter measurement failure was substituted by data of DDC-controlling or internal heat balance calculations.
3) Solar heat supplied into network: sum of direct used solar heat plus heat discharged out of aquifer (direct supply and on part of evaporator before the heat pump)
4) Based on total heat demand

In figure 7 the measured temperatures of the ground are shown at a distance of 5 m from the hot well in flow direction of the ground water at different dates. At the end of the charging period in August the store reaches its highest temperature. The inhomogeneous temperature propagation results from the inhomogeneous ground structure.

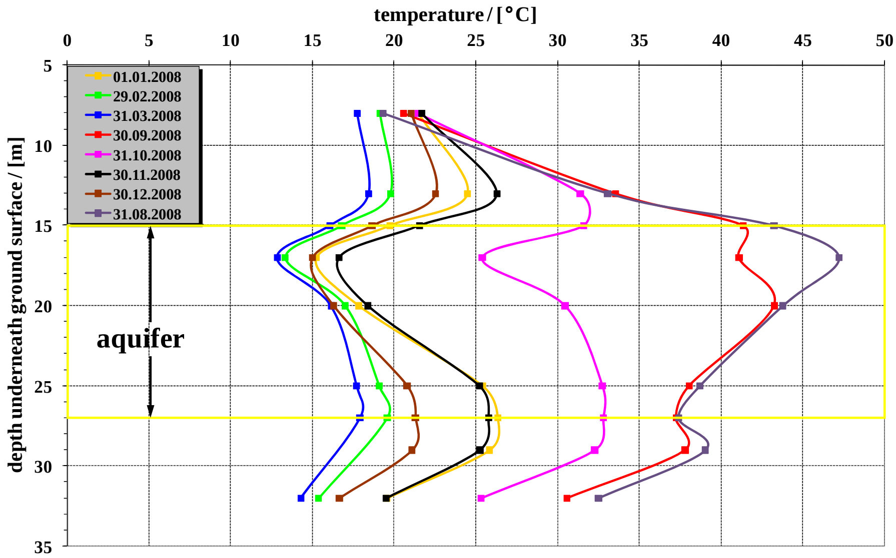

Figure 7: Ground temperature in the aquifer at a distance of 5 m from the hot well in ground water flow direction at different dates in 2008

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