AQUIFER THERMAL ENERGY STORAGE – PROJECTS IMPLEMENTED IN GERMANY

P. Seibt and F. Kabus
Geothermie Neubrandenburg GmbH
D-17033 Neubrandenburg, Seestrasse 7 A
phone +49 395 3677412
e-mail gtn@gtn-online.de

1. INTRODUCTION

Seasonal thermal energy storage is an important and often decisive component of the development of promising and innovative energy supply concepts. An interesting technique is the storage of thermal energy in aquifers. The seasonal storage of thermal energy in aquifers allows for the shifting of solar energy, surplus industrial waste heat and heat arising from cogeneration plants for the heating of buildings from summer for use in winter.

Another interesting application of aquifer thermal energy storage is the storage of ambient cold in winter for air conditioning in summer. A complete storage cycle (injection, storage and recovery) was successfully tested in a shallow aquifer at Dresden (SE Germany) in 1983 already.

The application on an industrial scale started in the 1990s after extensive preliminary investigations. In the following, the first field test and three working systems are presented and in addition, the operational experience gathered so far is described, respectively.

1. ATES TECHNIQUE

Mode of functioning

As a rule, such a store unit consists of two wells or groups of wells developing the same aquifer. They are arranged at an internal distance of 50 ... 300 m in order to exclude mutual thermic influencing. Both wells are equipped with pumps and an injection string allowing the unit to be flown through in either direction. Heat exchangers integrated in the surface pipe system connecting the wells allow for the feeding and supply of thermal energy. The water produced via the cold well is heated up in summer, e.g., with waste heat and injected in the warm well forming a so-called heat bubble in the aquifer. In winter, the heat is recovered from this heat bubble in the reverse direction of flow. Analogously – seasonally shifted only – a cold store is operated in the aquifer.

Geological and licensing conditions

The geological conditions at the site concerned are of decisive importance for the design and installation of aquifer thermal energy stores. The mainly used water-bearing pore spaces (aquifers) must provide sufficient flow properties allowing flow rates from 10 ... 100 m³/h for the production and injection via one well, respectively. Based on the knowledge on groundwater production, the determination of the hydraulic properties of the porous groundwater-bearing beds is relatively easy, however, it requires site-specific investigations. Then, the hydraulic and thermodynamic behaviour of the stores can be prognosticated over longer periods of time by means of existing groundwater models.

The results of investigations implemented within the framework of a project supported by the European Commission showed that aquifers suitable for thermal energy storage exist on approx. 70 % of the overall territory of Germany. The investigations were limited to a depth of 150 m (DIS-0463-95-NL (1997)). This natural potential is enhanced by using even deeper aquifers which has been done recently.

Principally, aquifers (groundwater-bearing beds) which are intended for thermal energy storage should come up to the following requirements:

- Max. depth of 1500 m:
  At present, a depth of up to 200 m represents the most favourable variant for the installation of low-enthalpy stores in terms of cost.
- Covered (confined) groundwater-bearing bed:
  On condition that adequate technological storage parameters are selected, even phreatic aquifers can be used according to most recent studies.
- Max. effective reservoir thickness approx. 30 m:
  If thicker, special production techniques would be required due to the horizontal propagation of the thermal front.
- Homogeneous aquifer structure:
  Strong interstratification may result in a smaller coefficient of recovery.
- Geometrical aquifer structure:
  Major differences in level relative to the aquifer top may lead to problems when re-producing the fluid accumulating in the top sections.
- Low regional base flow or detailed knowledge on the regional groundwater flow parameters:
  Appropriate siting of the wells can influence the propagation of the thermal front which is important for longterm operation.
- Appropriate chemical composition of reservoir fluid (heat transfer medium) and matrix:
  Changes of the state in the working section of the reservoir must not affect reinjection.
- Store installation out of groundwater catchment areas:
  Interference and quality impairment must be avoided.

As regards the licensing of aquifer storage at depths < 100 m in Germany, the Water Management Act (WHG – Wasserhaushaltsgesetz) incl. its ordinances and relevant regulations of the Federal States are applied. At depths > 100 m, the regulations of the Federal Mining Code (BBergG – Bundesberggesetz) are applicable.

**Technical integration in the systems**

The integration of underground stores in supply systems presupposes detailed considerations regarding the behaviour of the quantities and temperatures of heat and cold demand or surplus. This results from the fact that the charging temperature and the duration of storage of each partial amount of heat influence the utilisation ratio of the store and that, within this context, the discharging temperature does not present any constant value. It is characteristic that discharging starts slightly below (in the case of cold discharging above) the mean charging temperature with the temperature decreasing then slowly (increasing when storing cold). In each case, the receiving heating installations must be dimensioned for a low temperature level, and the receiving cooling installations – for a high temperature level.

In the following, two essential applications of the underground thermal energy storage are described. Often, high-temperature surplus heat cannot be directly used in summer. This refers to solar thermal units, cogeneration plants, industrial waste heat, etc. In the case of the solar unit, heat is stored in summer and fed back in winter to cover the base load of the heating system. But when the surplus heat is supplied by a cogeneration plant, then it has to be considered when designing the discharging of heat that the base load of the consumer system is covered by its waste heat, too. Figure 1 presents the distribution of surplus and demand for cogeneration plants and solar thermal units, respectively.

![Figure 1: Demand / surplus scenarios (red – energy demand, orange – surplus energy)](image-url)
5. APPLICATION OF ATES IN GERMANY

Immediately after the oil crisis in the early 1970s, extensive research and development programmes for efficient energy storage techniques were launched in Germany and other industrialised countries. The results of the investigations indicate that thermal energy storage (mainly low-temperature heat or cold) in groundwater-bearing layers (aquifers) is very promising and implementable at favourable cost.

First field tests were carried out in Germany already in the early 1980s.

The application on an industrial scale started in the 1990s after extensive preliminary investigations. Within this framework, quite a number of sites was examined and explored geologically. (SEIBT et al. (1996)). The technical breakthrough was achieved in 1995 with the integration of two aquifer thermal energy stores in the energy supply system of the buildings of the German Parliament in the centre of Berlin (KABUS&SEIBT(1997)). Table 1 summarises the most important hydrogeological parameters of the described aquifers.

<table>
<thead>
<tr>
<th>Site</th>
<th>Dresden (Field test)</th>
<th>Rostock-Brinckmanshöhe</th>
<th>Buildings of the German Parliament in Berlin</th>
<th>Neubrandenburg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geological Formation</td>
<td>Quaternary</td>
<td>Quaternary</td>
<td>Hettangian</td>
<td>Upper Postera</td>
</tr>
<tr>
<td>Depth</td>
<td>7m-10m</td>
<td>13m-27m</td>
<td>285m-315m</td>
<td>1234m-1274m</td>
</tr>
<tr>
<td>Porosity</td>
<td>~25%</td>
<td>~20%</td>
<td>30%</td>
<td>~30%</td>
</tr>
<tr>
<td>Permeability</td>
<td>&gt;2 µm²</td>
<td>8 µm²</td>
<td>2.8 – 4.2 µm²</td>
<td>&gt;1 µm²</td>
</tr>
<tr>
<td>Mineralisation</td>
<td>Freshwater</td>
<td>Freshwater</td>
<td>29 g/L</td>
<td>133 g/L</td>
</tr>
<tr>
<td>Store temperature (initial)</td>
<td>8°C</td>
<td>10°C</td>
<td>19°C</td>
<td>10°C</td>
</tr>
<tr>
<td>Store temperature (end)</td>
<td>54°C</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Hydrogeological parameters of the aquifer thermal energy stores

**Dresden Field test**

The first field test covering a complete storage cycle (injection, storing, recovery) was carried out at Dresden in 1983.

A group of wells existing on the territory of the Dresden University of Technology and comprising 24 groundwater monitoring pipes could be used for the field test. For that, adequate data logging equipment was installed, and a test unit for the production, heating-up and injection of the groundwater was built.

In 21-day period of injection, totally 2,189 m$^3$ of water with a temperature of 40 °C were injected in a 3 m thick groundwater bearing bed at a depth of 10 m. After a storage period of 10 days, 3,577 m³ of water were re-produced over a period of 36 days. At the end of discharging, the coefficient of recovery was 0.56.

Throughout the entire test period, the temperature was measured continuously via 25 measuring heads at different depths. The findings concerning the time- and site-dependent temperature behaviour served to review the simulation of the store.

For the simulation of the thermodynamic behaviour of the heat store, a semi-analytical method (solution in the Laplace-transformed section) was developed describing beside the injection for the first time also storage and recovery (SEIBT et al. (1990)).

**Residential complex „HELIOS“ at Helios in Rostock-Brinckmanshöhe**

The building complex built at Rostock-Brinckmanshöhe in 1999/2000 houses 108 flats with a total area of approx. 7,000 m². Totally, 320 MWh/a are needed for heating and additionally 180 MWh/a for sanitary hot water (SHW) preparation.

According to the requirements of the design, clearly more than 50 % of this total heat demand was to be covered by solar thermal energy use. This could be implemented only by integrating a seasonal heat store.
On the 11 individual roofs of the building complex, solar collectors are installed which are directed towards south with an inclination of 38°. This “solar roof“ has a total absorber surface of 1,000 m². In summer, the collectors supply 400 MWh of solar heat.

A covered groundwater-bearing bed exists under the site at a depth of approx. 15 ... 25 m. This aquifer is developed by two wells with an internal distance of approx. 55 m. The water produced via the cold well with a temperature of 10 °C is heated up in summer by solar energy and injected in the warm well. In winter, the direction of flow is reversed. At the beginning, the production temperature is 45 °C. In the course of the heating period, the temperature decreases down to the natural groundwater temperature.

After the direct heat exchanger for pre-heating of the return flow in the heating system (low-temperature system with 45 °C/30 °C, outdoor temperature-driven) and of the sanitary hot water, an electrically driven 100 kW heat pump is integrated transforming the groundwater temperature onto a usable level.

After a running-in period of approx. 3 years, a coefficient of the recovery of the stored heat amounting to approx. 63 % was achieved (BARTELS & KABUS (2003)).

Buildings of the German Parliament in Berlin

Several differently shaped aquifer thermal energy stores are integrated in the energy supply system of the buildings of the German Parliament in the Spree river curve in Berlin.

The heat energy arising from the own generation of power in block-type cogeneration plants at a temperature level of 110°C serves for direct heat supply in the high-temperature (90°C/60°C) and partly in the low-temperature heating networks (45°C/30°C) and, moreover, the driving of coolers / heat pumps.

Since the heat and power demand behaviour is not synchronous, more heat than required is offered by the cogeneration plant temporarily, and at other times less amounts of heat than needed to cover the demand can be supplied. That is why surplus waste heat arising from the cogeneration plants is seasonally stored in an approx. 300 m deep brine-bearing aquifer heat store. The hydraulic properties of the aquifer allow for the pumping of max 100 m³ of brine per hour via one deep well or reinject the same quantity. The waste heat is fed into the store with a temperature of 70°C and recovered with 65°C...20°C at a later date, supplying then in direct heat exchange the low-temperature section of the heating systems. Absorption-type machines serve for further cooling of the store transforming the heat onto the temperature level of 45 °C.

Another underground store is integrated in the concept which is located at a depth of approx. 60 m, i.e., at the freshwater level. This aquifer cold store serves primarily to cool the buildings. Totally, 300 m³ of water are circulated per hour via 10 wells.

In winter, the water contained in the cold store is cooled down to minimum 5 °C. On the one hand, this is done by feeding cold into the store via recooling units on days with low outdoor temperatures. On the other hand, the cold store serves along with the heat store as source to the absorption-type heat pumps, which absorb its heat thus decreasing its temperature.

The cold stored in this way in winter supplies in summer via heat exchangers the high-temperature cooling systems of the buildings at a temperature level of 16°C/19°C.

By means of the practical implementation of the described concept the block-type cogeneration plants covering 37 % of the electrical peak load generate 82 % of the electric work and even 90 % of the heat required per year. 60 % of the cold demand in summer are covered by the cold store (KABUS & SEIBT (1998)).

Neubrandenburg

Since 1987, a geothermal heating station supplies heat to a district heat supply network at Neubrandenburg. For the production and injection of the required amount of thermal water (150 m³/h with approx. 53 °C and a mineralisation of 120 g/L), four wells were available drilled down to depths between 1,200 m and 1,300 m. The direct heat exchange was supported by an absorption-type heat pump and conventionally fired boiler units.

In 1997, a gas and steam turbine-driven power plant was commissioned cogenerating 77 MW of power and 90 MW of heat.
However, the advantages of the gas and steam cogeneration plant become effective only when both kinds of energy can be used when generated. Therefore, it was obvious to store the surplus heat arising from the cogeneration plant in summer in the aquifer of the geothermal heating plant.

The decision was pushed very much by the fact that the wells of the existing geothermal plant urgently needed rehabilitation (caused by the poor quality of the materials available in 1986 only) and the low efficiency due to the relatively low thermal water temperatures and the small heat sales in summer.

After retrofitting of the geothermal heating plant as an aquifer thermal energy store including two deep wells, the temperature level of the geothermal reservoir could be elevated with the waste heat arising from the gas and steam cogeneration plant. Consequently, the absorption-type heat pump became obsolete.

The heat store is in operation since April 2004. In the heating period 2004/2005, heat could be recovered from the store for the first time. The surplus heat arising from the cogeneration plant in summer which has been led by now to the cooling towers is now fed into the centralised primary district heating network and supplied from here up to the geothermal heating station.

In winter, the heat store is operated as before the geothermal heating plant. Thermal water is now produced from the „warm“ well for heating of the residential area „Rostock Street“. Then it is led to the drilling field at Broda and injected via the „cold“ well. The essential difference compared to the hitherto geothermal operation is that the production temperature of the thermal water is not around 50 °C anymore, but 70 °C ... 80 °C.

Under the frame conditions
- maximum thermal water flow 100 m³/h
- charging temperature 80°C
the thermodynamic calculations resulted in a storage potential of 12,000 to 20,000 MWh of heat from April through September. In winter, i.e. from October through March, up to 10,000 MWh are recovered.

Table 2 gives a summary of the most important dimensioning parameters of the aquifer thermal energy stores.

<table>
<thead>
<tr>
<th>Site</th>
<th>Rostock-Brinckmanshöhe</th>
<th>Buildings of the German Parliament, Berlin</th>
<th>Neubrandenburg</th>
</tr>
</thead>
<tbody>
<tr>
<td>heat source</td>
<td>solar energy</td>
<td>waste heat arising from a biodiesel-driven cogeneration plant</td>
<td>ambient cold</td>
</tr>
<tr>
<td>aquifer store:</td>
<td>heat store</td>
<td>heat store</td>
<td>cold and heat store</td>
</tr>
<tr>
<td>- shaping</td>
<td>doublet</td>
<td>doublet</td>
<td>2*5 wells</td>
</tr>
<tr>
<td>- max. flowrate</td>
<td>15 m³/h</td>
<td>100 m³/h</td>
<td>300 m³/h</td>
</tr>
<tr>
<td>- charging temperature</td>
<td>50°C</td>
<td>70°C</td>
<td>5°C</td>
</tr>
<tr>
<td>consumer systems:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- connected load</td>
<td>0.25 MW</td>
<td>12.5 MW</td>
<td>7.0 MW (cold)</td>
</tr>
<tr>
<td>- energy demand</td>
<td>495 MWh/a</td>
<td>16,000 MWh/a</td>
<td>5,000 MWh/a</td>
</tr>
<tr>
<td>- network temperatures</td>
<td>65°C (SHW)/45°C (heating)/30°C</td>
<td>45°C/ 30°C (heating)/14 °C/ 19 °C/ 80°C/ 45°C</td>
<td></td>
</tr>
<tr>
<td>energy balance (design):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- energy charge</td>
<td>234 MWh/a</td>
<td>2,650 MWh/a</td>
<td>4,250 MWh/a (cold)</td>
</tr>
<tr>
<td>- energy discharge</td>
<td>148 MWh/a</td>
<td>2,050 MWh/a</td>
<td>3,950 MWh/a</td>
</tr>
</tbody>
</table>
Table 2: Dimensioning parameters and energetic target values of the working aquifer thermal energy stores

<table>
<thead>
<tr>
<th></th>
<th>(with re-cooling)</th>
</tr>
</thead>
<tbody>
<tr>
<td>- coefficient of recovery</td>
<td>63%</td>
</tr>
<tr>
<td></td>
<td>77%</td>
</tr>
<tr>
<td></td>
<td>93%</td>
</tr>
<tr>
<td></td>
<td>72%</td>
</tr>
<tr>
<td>- percentage of the stored energy in the coverage of the demand</td>
<td>30%</td>
</tr>
<tr>
<td></td>
<td>13%</td>
</tr>
<tr>
<td></td>
<td>55%</td>
</tr>
<tr>
<td></td>
<td>48%</td>
</tr>
</tbody>
</table>

6. OPERATING EXPERIENCE

Meanwhile, almost all the systems described above have passed the running-in phase of 3 to 5 years which is required for seasonal aquifer thermal energy stores. The thermic situation in the underground has reached a stationary condition. Certainly, the most important result is the chemically and hydraulically stable operation of the store loops - precipitation and deterioration of the injectivity are known reasons for the failure of such systems.

The experience gathered over decades in the field of the reinjection of cooled thermal brines in sandstone aquifers laid a solid foundation (HEEDERIK et al. (1996), SEIBT & KELLNER (2003)). Basically, this refers to the filling of the system with protective gas (nitrogen), thermal water filtration and geochemical simulation of the precipitation behaviour for determination of the optimum pressure stage as well as the maximum feeding temperature (SEIBT et al. (1998)).

The working data of the described plants allow for the proof of reliable operation throughout several years and reliability of the design and prognosis tools for the thermal and hydraulic behaviour of the aquifer stores. In particular, this refers to the numerical simulation of the underground based on continuous recording of the relevant parameters of operation, which is presented in Figure 2 by means of the example of the heat and cold stores of the buildings of the German Parliament in the Spree river curve in Berlin.

The operating experience for the heat store at Neubrandenburg are of particular interest due to the large quantities to be stored and the specifics of the coordination with a district heat supply network supplied by a cogeneration plant which is unflexible due to its extension. Within the framework of an accompanying R&D project, concepts are being developed for optimisation of the store integration.

The essential results of the first charging and the rather short discharging phase of this aquifer store are shown in Figure 3. Already in the first year of operation, a mean production temperature of 70 °C instead of the natural thermal water temperature of 52 °C was available in the discharging cycle over a longer period of time. The by then in January and February required operation of a heat pump could be abstained from. A more detailed description of the operating experience is given by KABUS et al. (2005).
The following generalisable conclusions result from the above:

- The existing numerical models for the description of the hydraulic and thermodynamic behaviour produce very exact prognoses. They can be applied even in operation in order to give the respectively optimum regime. The condition is very thorough monitoring of the operation.
- Suitable technical measures (indication of temperatures and pressures to be observed, no entry of oxygen, selection of adequate materials, filtration, defined starting and ending as well as switching regimes) help to guarantee stable and safe operation over long periods of time.

Aspects of the correct integration and later proper operation of the store in the concert of all elements of the energy supply system are at least of the same importance for the acceptance of a heat store along with the geoscientific and technical detailed solutions.

7. CONCLUSIONS

Evaluating the plant operation so far it has to be stated that the design, installation and operation of an aquifer store at suitable sites can be implemented, duly exhausting the existing geological, geotechnical and technological potentials for the efficient operation of these stores. The heat store units can contribute essentially to the increase of the efficiency of the overall system as well as to the reduction of CO\textsubscript{2} emission. Thanks to the licenses granted in Germany now for underground stores under the Water Management Act and the Mining Code, there do exist in the mean time clear conceptions concerning the content and course of the licensing procedure. Thus, good chances are given for the application of these innovative and environmentally benign energy storage techniques in Germany.

ACKNOWLEDGMENTS

The projects at Rostock – Brinckmanshöhe and Berlin were supported by the Federal Ministry of Economics of Germany. At present, the Federal Ministry of Economics supports monitoring programmes for the projects at Berlin and Neubrandenburg. The investigations into the geological potentials and the reinjection of thermal waters into sandstones were supported by the European Commission.

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