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Advantages and problems of high temperature underground thermal energy storage

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ABSTRACT

Underground Thermal Energy Storage (UTES) on temperature levels above ca. 50 °C is still not done widely today. The development harks hack to the 70s, hut the real breakthrough still has to he made. Nevertheless, some very interesting plants are operational, and a lot of experience was gained through experimental and theoretical work. In a report in IEA ECES Annex 12 this experience is documented, and the needs and opportunities for future R&D and applications are identified. This paper summarises the IEA report and highlights some system opportunities identified within the IEA co-operation.

KEYWORDS

UTES, underground heat storage, aquifer storage

1. Introduction

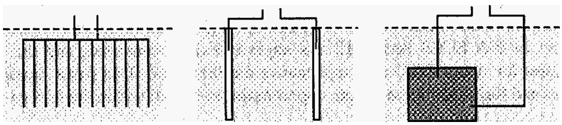
Heat storage is a crucial issue to match demand for heat with supply of heat, or even with the need to get rid of waste heat. The ground has proven to he an ideal medium for storing heat in larger quantities and over longer time periods, like the yearly seasons. After plants to store summertime solar heat for use in winter heating, storage of waste heat now is emerging. The efficiency of heat storage depends upon the temperature level achieved and upon minimization of thermal losses. While heat storage in the range of 10-40 "C has been demonstrated successfully, higher temperature levels up to ca. 150 "C have caused a lot of problems in experimental and pilot plants in **the** 80s. Following a revival of interest in subsurface heat storage, a new activity of the International Energy Agency (IEA), called ECES Annex 12, was launched in December 1997 to address high temperature underground thermal energy storage. In a first phase, information from the past experimental and pilot plants was collected, and a survey concerning operational experiences, technical problems, environmental behaviour and economic and ecologic advantages was made. The area of investigation is confined by some definitions:

- Underground Thermal Energy Storage comprises all storage of heat, cold, or both in the natural underground (i.e. rock, soil, groundwater, caverns, pits etc.). Not included are artificial structures built below ground, like buried tanks.
- High Temperature Underground Thermal Energy Storage refers to minimum storage loading temperatures on the order of 50 "C.
- Storage may be from short term (diurnal) to long term (seasonal), whereas "seasonal" requires the store to yield energy recovery at least three month after end of the loading period.

Within the IEA Energy Storage Programme (ECES), some acronyms are widely used, and are also applied in this text:

UTES	Underground Thermal Energy Storage (in general)
ATES	Aquifer Thermal Energy Storage (groundwater as heat carrier)
BTES	Borehole Thermal Energy Storage (systems with boreholes and pipes)
CTES	Cavern Thermal Energy Storage (Artificial openings in the rock)

Also the term BHE (for Borehole Heat Exchanger) is used here. The main underground concepts are explained in Fig. 1.



Borehole Storage

Important Parameters:
- high specific heat
- medium therm. cond.
- no groundwater flow

Examples:
- Sediments like shale, marl, clay etc.; limestone, sandstone end others may also be suitable
- Igneous rocks like granite, gabbro etc., some metamorphic rocks like gneiss too.

Aquifer Storage

important Parameters:
- medium to high hydr. cond. and transmiss.
- high porosity
- low or none groundwater flow

Examples:
- Porous aquifers in sand, gravel, eskers
- Fractured aquifers in limestone, sandstone, igneous or metamorphic rock

Cavern Storage

important Parameters:
- low therm. conduct.
- high rock stability
- rock not leachable

Examples:
- Gneis, granite, other igneous rocks, hard sedimentary rocks

Figure 1: Different generic types of UTES

The first publications are from the 1960s, and frst experiments are reported from the 1970s (Kley & Nieskens 1975; Mathey 1977; Molz et al. 1979). Around 1982, several pilot plants were constructed, and most are well documented. Table 1 gives some examples and lists also recent demonstration plants. The depth of wells for ATES does not exceed 400 m, and is usually much shallower, while depth of borehole heat exchangers ranged between 30 and 100 m. As evolution from the underground alternatives shown in Fig. 1, the use of deep aquifers (>1000 m) as well as deep borehole heat exchangers (>1000 m) was considered recently. With increasing depth, the ground temperature is higher. This limits thermal losses, but storage changes gradually into pure geothermal heat extraction at greater depth.

Table 1: Selected High Temperature UTES pilot and demonstration plants (beside the first three, no pure experimental plants and no caverns are listed; a full list and the references can be found in Sanner & Knoblich 1998)

Year	Name/Location	Max. temp.	Remarks
1982	SPEOS, Lausanne-Dorigny, Switzerland	69 °C	Waste incineration, ATES, closed
1982	Hørsholm, Denmark	100 °C	Waste Incineration, ATES, closed
1982	University of Minnesota, St. Paul, USA	115 °C (150 °C)	ATES, experiment, aquifer at ca. 180-240 m depth, closed
1983	Luleå Techn. Univ., Luleå, Sweden	65 °C	Industrial Waste Heat, 121 boreholes, closed
1984	Groningen, The Netherlands	50 °C	Solar Heat, 360 Borehole Heat Exchangers, in operation
1991	De Uithof, Utrecht Univers. Utrecht, The Netherlands	90 °C	Waste heat from heat and power co-generation, ATES, in operation
1998	Hospital "Hooge Burch", Gouda, The Netherlands	ca. 90 °C	Waste heat from co-generation, ATES, in operation
1998	Amorbach, Neckarsulm, Germany	ca. 70 °C	Solar Heat, 168 Borehole Heat Exchangers, in operation
1999	Reichstag building and offices, Berlin, Germany	ca. 70 °C	Waste heat from heat and power co-generation, ATES, in operation

2. Results of IEA ECES Annex 12

The following conclusions from Phase 1 of IEA ECES Annex 12 were prepared in two expert's meetings in 1998 and finished through intensive review in the Annex 12 group and by other experts. Three main areas are covered

1. What can we learn from the past experiences, be it experimental or demonstration? What were the main problems encountered?

2. What are the key areas, where further R&D is required to solve remaining problems, and what are the concrete topics? (only topics should be addressed, which have a realistic chance to be successfully solved)
3. What are promising system concepts, in what circumstances can HT-UTES best show its potential, i.e., why is it worthwhile to continue with R&D in this field?

A general conclusion can be made: HT-UTES is required to allow direct use of stored heat, without further energy input, e.g. for heat pumps. If high temperature heat is available from clean sources (solar collectors, geothermal) or as waste, the overall result of HT-UTES-operation is always favorable. The remaining problems all seem to he not too hard to be solved, and other limitations may present no drawback for the moment. Some new plants recently became operational, after a longer break, and more new projects are under serious consideration. The Annex 12 expert's group expressed an optimistic view for the future of HT-UTES.

2.1 Operational experiences from existing HT-UTES-plants

Some general remarks can be made: Most of the systems under investigation run, but the users usually do not know if they run at optimum or even well. *So* monitoring and evaluation is crucial to find the flaws in system design, construction, and operation. Good to optimum operation on the other hand is required for long-term sustainable performance. In the demonstration plants, energy demand was mostly not as designed (usually lower), and this affected storage efficiency.

Minimum monitoring required is temperatures, water and energy flows in the surface installation. A monitoring period should last at least *2* loading/unloading cycles. Monitoring may also act as an early warning system, identifying problems like well clogging at an early stage. Storage efficiency and temperature are the key points for economic and energy saving operation. Here it was found through monitoring, that the unloading temperature can he lower then calculated, e.g. due to unexpected buoyancy flow (free convection). Two examples (s. Tab. 1) were investigated in more detail:

- Lulea: The predicted storage efficiency was not achieved in the first year, the reason was a construction error with the de-aeration system. After fixing, only minor problems occurred.
- Utrecht: Return temperature from buildings was to high, thus minimum design unloading temperature was not met and unloading of the store was less than designed. Energy demand at lower temperature level was not as high as in the design.

User behavior has shown to he a crucial issue; e.g. users made changes without consulting the designer or even telling him. A surprising fact was, that user interference was mostly beneficial (e.g. in Utrecht). User education nevertheless is important, and on the long term, user interference should he limited, to prevent errors.

The experiences with water treatment systems were of particular interest for aquifer storage. Concerning Fe/Mn-scaling, the only possibility is to keep the system under pressure. If mixing of waters in the ground is possible, no ATES should be built. Keeping the system under pressure is also the only possibility to prevent gas clogging, while degassing units may be a solution in future. A selection of methods is available against carbonate scaling, like Na^+ ion exchange, addition of acids (HCl, but no HNO_3, H_3PO_4 or H_2SO_4, which may act as nutrients for bacteria), addition of CO_2, or the fluidized bed heat exchanger. Only Na^+ ion exchange and addition of HCl were used successfully in full-scale plants by now.

Main technical problems encountered in the existing plants were:

- Control system (in Utrecht later upgraded by user)
- Deep shaft pumps (better to use submersible pumps)
- Frequency controllers with long cables (electromagnetic noise)
- Sensors (in particular flow meters)
- Surface connections (pipes)
- Problems with Heat Pumps (e.g. in Lulea)
- Cracking of confining layer due to high pressure
- Corrosion, if material is not adequate
- Well clogging problems due to inadequate or not working water treatment system.

2.2 Recommendations for further R&D on system studies and technical problems of HT-UTES

A system analysis should be done on the base of a collection of (recent) results of feasibility studies, allowing comparison and evaluation of configurations.

Operational strategies need further investigation, incl. the verification of storage loading etc., and suitable control systems for the storage system in toto have to be optimized. As support, existing simulation models for plant design and for evaluation of operational strategies have to he adapted and used.

There are several R&D-needs concerning individual components and worksteps:

- Drilling, incl. fracturing of rock to increase hydraulic conductivity (for ATES)
- Submersible pumps for high temperatures (at affordable prices)
- Suitable pipe materials for high temperatures, especially plastics
- Material and technique for insulation on top of store, especially for shallow BHE
- BTES: U-tube design is used for low temperatures and low At; modeling and experiments concerning applicability at high temperatures are required, incl. an optimization of design and evaluation of alternatives (e.g. concentric)
- ATES: Well layout optimization
- Fluidized bed heat exchangers have to be made feasible at a technical scale
- For water treatment optimization in ATES plants, some urgent issues have been identified
  - Automatization of treatment processes
  - For the CO_2-treatment, the importance of stripping of CO_2 in the unloading process has to be investigated
  - Scaling inhibition with natural inhibitors has to be understood better and may be used in practice
  - Mobile Test Equipment for planning of adequate water treatment methods at individual sites should be developed

- Concerning environmental issues, the temperature impact and changes in water chemistry should he considered more closely (in particular long-term effects), and should he investigated through monitoring in existing plants.

2.3 System opportunities and chances for increased application of HT-UTES

Possible heat sources and heat users are listed in Tab. 2. Promising systems can be divided into two groups:

a) From renewable sources:

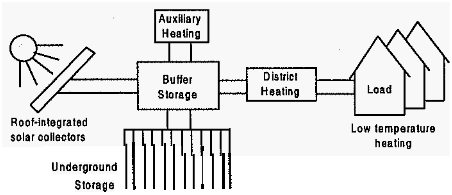
Heat source can he solar heat (always with buffer store to level short-term changes), with direct heat supply to the district heating network, and backed by an auxiliary heating system (Fig. 2, above), or with heat pumps, were the auxiliary system may not he required (Fig. 2, below). Another option may be the **use** of geothermal heat, allowing storage of excess production **in** summertime and covering of **peaks** in winter, or for using waste heat from geothermal power plants (Fig. **3)**

b) From waste or excess heat:

Storage **of** waste heat from co-generation or industrial processes (Fig. **4** left) may he on a seasonal cycle. UTES can also be applied as a back-up in industrial waste heat **use,** to cover heat load while the industrial process is stopped; the store is always kept loaded, to provide heat in times of production breaks, repairs, etc. (Fig **4** right). Similar is the **use** for load leveling in a district heating system, where the store is always loaded at times **of** low heating demand, and unloaded during peak heating periods. The schematic is similar to Fig. 4 (right).

Table 2: Possible heat sources and heat users for High-Temperature UTES

Possible heat sources	Possible heat **users**
Renewable energy. - Solar thermal (solar collectors, but also road surfaces etc.) - Geothermal (hydrogeothermal, but also waste heat from geothermal power plants, e.g. Hot Dry Rock) - Others (biofuels?)	Space heatmg - District heatmg - Large buildings (housing, offices, hospitals, hotels, airports, etc)
Waste heat - Heat and power co-generation (only *with* high electrical efficiency!) - Industrial / process heat (paper **mills,** steel works, and others) - Waste incineration - Others	Industrial heat - Batch or seasonal processes like **in sugar** refineries - Drying in food industry - ***Most*** *industries* have excess heat, thus no use for UTES Agriculture - Greenhouse heatmg - Drying **of** grain, hemp, grass (hay), etc - Aquaculture
Load leveling in district heating systems (short- to medium term)	*De-icing* and *snow-melting* ***on*** roads, sport centers, airports/run-ways, etc



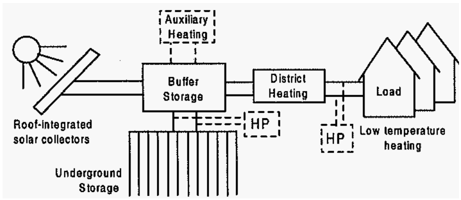


Figure 2: Solar heat storage with direct (above) and heat-pump-supported (below) unloading of the store

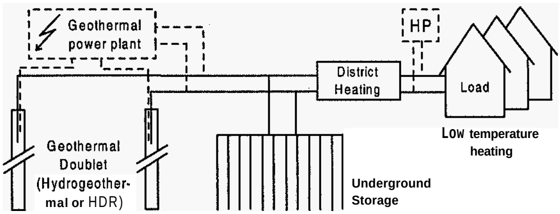


Figure 3: Geothermal heat storage

3. Conclusions

The study showed, that technical problems related with higher temperatures in UTES system may be overcome. One main issue still are the changes in water chemistry with drastically changing temperatures in ATES systems, resulting in clogging, scaling, corrosion and leaching. It is possible to design and build reliable High Temperature UTES plants today, but caution is necessary when working with groundwater. In future, the existance of a choice of suitable methods for various hydrogeological/hydrochemical situations and system requirements is desirable. The investigation of promising system concepts revealed a number of opportunities to make use of UTES for saving energy and reducing emissions.

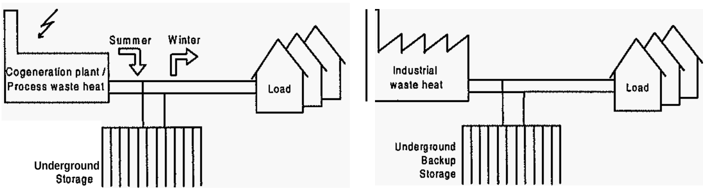


Figure 4: Waste heat storage, seasonal (left) or backup (right)

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