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Underground Thermal Energy Storage (UTES)

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1. Introduction

We have utilized the underground since the beginning of mankind. One very early observation was that the ground temperature was often very different from the air temperature. It was found out that the underground could serve as protection not only from enemies, but also from the coldest days of the winter and the hottest days of the summer.

The ground temperature at a certain depth below ground surface (10-15 m), which is not influenced by the season temperature variation at the surface, is equal to the annual mean air temperature. There are many examples, from various regions of the world, of ancient underground buildings with comfortable temperatures around the year. Such buildings have often one outer wall while the others are surrounded by rock or soil.

Fig.1. Occurring stable ground temperatures are utilized in Cappadocia (Turkey) where there are numerous buildings excavated in the mountains. The surrounding rock provides cooling in summer and heating in winter.
http://www.bertur.pl/kapadocja-turcja4.jpg

A more recent underground thermal storage technology, developed during the last 40-50 years, means that thermal energy is actively stored for the purpose of later extraction. So, heat is either injected for later use (heat storage) or extracted from the ground (cold storage) which is later used for cooling. Such thermal energy storage is mainly for long-term storage or seasonal storage of thermal energy storage. There are also combinations in which the storage is used for both short-term and seasonal storage.

There are a number of such technologies summarized by the acronym UTES (Underground Thermal Energy Storage).

- Aquifer Thermal Energy Storage (ATES)
- (Rock) Cavern Thermal Energy Storage (CTES)
    - Snow Storage Systems
- Borehole Thermal Energy Storage (BTES)
    - Thermal Response Test

International research and collaboration on thermal energy storage has been carried out for more than 30 years within the framework of IEA (International Energy Agency). This research is organized under the Implementing Agreement on Energy Conservation Through Energy Storage under which a large number of international research projects (Annexes) have been carried out. (**IEA ECES IA, 2012**)

2. Aquifer Thermal Energy Storage

The operation of Aquifer Thermal Energy Storage (ATES) means that water is extracted from a well and is heated or cooled before it is re-injected into the same aquifer. So, the thermal energy is stored in the groundwater and in the matrix around it. There are usually several wells, for extraction and injection, and these are separated in order to keep the warm and cold water from mixing. ATES systems are large scale systems mainly for seasonal thermal energy storage both heating and cooling. In many cases the same ATES is used for both heating and cooling.

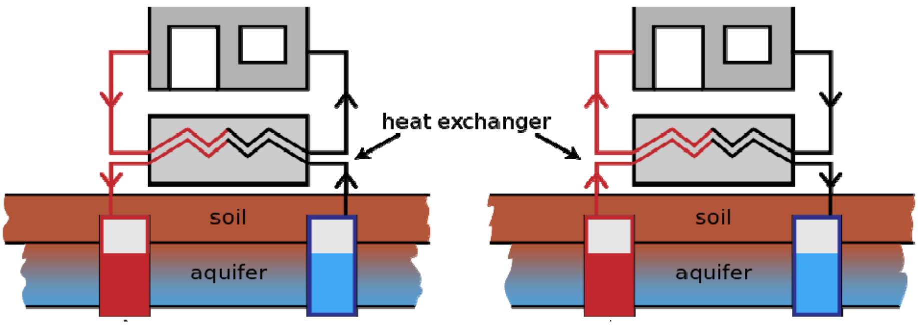


Fig.2. Outline of Aquifer Thermal Energy Storage system. [Ref. The Azimut Project].
Left/ Summer - the ATES is used for cooling. Right/ Winter - the ATES is used for heating.

A Workshop on Thermal Energy Storage in Aquifers in 1978 at the Earth Sciences Division, Lawrence Berkeley Laboratory, University of California, led to the creation of the ATES Newsletter. It became very soon after the first issue was published in October 1978 a quarterly newsletter.

The idea was that ATES Newsletter would supply speedy dissemination of new information, being a source of new ideas, and encouragement of personal contacts. When the field grew to include more storage types the name was changed to STES for Seasonal Thermal Energy Storage. Thanks to Ed Morofsky, at the Public Works and Government Services Canada, all issues of ATES and STES have later been made freely available (**ATES-STES ftp site)**.

This Berkeley workshop reflected the keen interest in alternatives to oil use, in the wake of the oil crisis in 1973. The workshop attracted fewer than 100 participants, and only a few of those were from outside of the USA. (**Nir, 1989).** Through the first editor of the ATES Newsletter, Chin Fu Tsang at Lawrence Berkeley Laboratory, it was made known that the ATES development started in China where it was used in a large scale already in the 1960ies.

Cold water injection into the aquifer was done during winter for summer cooling and heated water was also injected during the summer for winter heating. In 1984 there were 492 cold storage wells (10-12 inches in diameter) in Shanghai accepting 29 million cubic meters of water annually. Of these wells, 90% were used for both injection and extraction. These ATES systems supplied cooling textile mills, chemical works and other industrial plants, but also commercial buildings. The total annual cooling energy stored in Shanghai was about 1 100 TJ (0.3 TWh). Waste heat was injected at temperatures as high as 40°C. The recovery temperature in the winter reached 38°C **(Morofsky, 1994).**

A large number of countries were involved in ATES activities in the 1980ies. Many ATES systems were constructed in countries, or part of countries, with suitable geology. The Netherlands is the number one country in the ATES field and its dominating company is IF Technology bv, located in Arnhem.

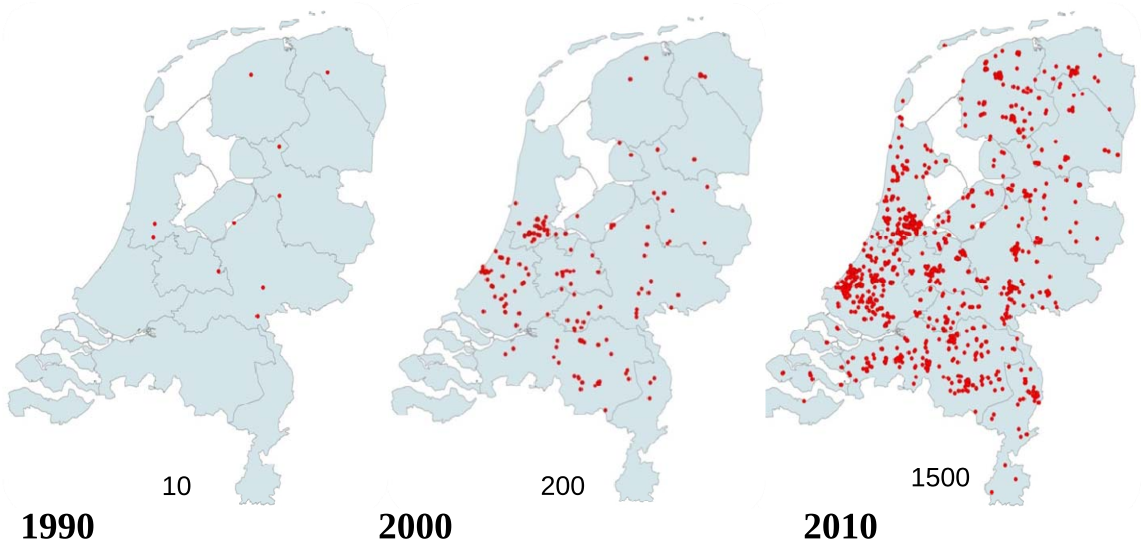


Fig.3. Map over the Netherlands showing the number of installed ATES in operation in 1990 (10), 2000 (200), in the year 2010 (1500). IF Technology estimates that the number of installed ATES system in the Netherlands will continue to grow until 2020. **(Bakema, 2010)**

3. Rock Cavern Thermal Energy Storage (CTES)

There are just a few examples of rock cavern thermal energy storages (CTES) in the world. The two first CTES actually built for this purpose were constructed in Sweden in the early 1980ies.

The Avesta storage with a water volume of 15,000 m^3 was made in 1980 for research while the 120,000 m^3 storage in Lyckebo is part of the Uppsala district heating system.

Three are also some examples of how to make use of old rock caverns, originally constructed for oil storage. The first one was made in Oulu, Finland, and another in Oxelösund, Sweden (Larsson, 2008).

The Oxelösund rock cavern (200 000 m^3) was converted to a hot water storage in 1988, to store industrial waste heat from the SSAB steel plant. For many reasons the storage is no longer in use (Ekengren, 1993).

The Oulu storage consists of two parallel rock caverns, with a total volume of 190,000 m^3, previously used as oil storage for the Kemira factory. Nowadays the caverns are filled with water and connected to Toppilas's cogeneration plant. Waste heat from the Kemira factory is also utilized in the district heating system. The waste heat power is about 10 MW. The rock caverns are used as seasonal heat storage for waste heat from the Kemira factory and as a short-term heat storage for the Oulu energy works. The Oulu energy works has already a steel tank heat storage with a volume of 15,000 m^3 for short-term storage. The maximum water flow rate for charging and discharging is 2500 m^3/h. A vertically moving diffusor with temperature following control system could be situated to the right temperature layer, when the heat storage is charged. It is unclear if the Oulu cavern is still in operation.

Although rock cavern heat storages have been demonstrated in full scale they are still too expensive to become an alternative to other hot water storage systems. Reconstruction of existing caverns or abandoned mines could however be make it economically feasible.

3.1 Seasonal Snow Storage (SSS)

Snow and ice have been used since ancient time for cooling during the summer. It was harvested in various ways during the cold season and stored until the warm season. The ice/snow was most often thermally insulated by sawdust. It is of course possible to use manmade materials for thermal insulation

In the north of Japan there are hundreds of snow cooling systems. They are several different types, most of for cooling of root vegetables, fruit, and vegetables. The snow is typically stored in the same building as the food stuff that is being cooled. There are also examples of snow storage rooms built close to residential building that is cooled during the summer**. (Skogsberg 2006, Kaneko et.al. 2009; Kobiyama 2009, Momota et.al. 2009)**

There are also some successful examples of recently built large scale snow cooling systems for cooling of commercial buildings. The large snow storage plant in Sundsvall utilizes 75,000 m^3 of snow in supplying cooling (4 MW; 3 GWh) for the Sundsvall regional hospital from May to September. Both of these plants have worked very well and deliver cold considerably cheaper than conventional cooling systems. The Sundsvall storage was taken into operation during the summer of 2000. **(Skogsberg, 2006)**

Another much larger plant was taken into operation in 2010 at the New Chitose Airport in Sapporo, Japan. This system which is inspired by the Sundsvall snow storage was made for 120.000 to 240,000 m^3 of snow corresponding to 5 to 10 GWh of cold. Published results are not yet available from this project. (**Hamada, 2012**)

Fig.4 The snow storage at the New Chitose Airport. Here, in May 2010, the snow storage (L: 200m, W: 100m, D: 2 m) is filled up and covered with thermal insulation. **(Seppyou, 2012)**

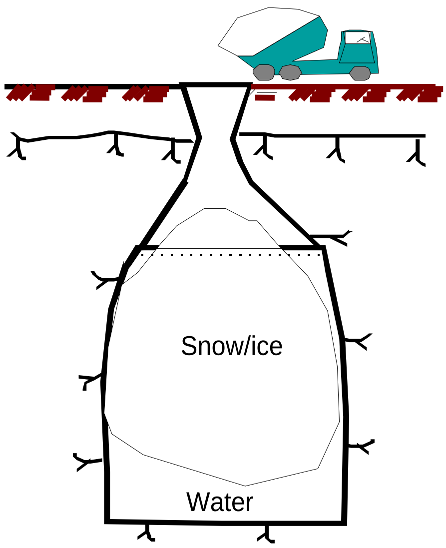


Fig.5 Outline of underground snow cavern.

The above mentioned three snow storage systems were all built in shallow pits on the ground. It is reasonable to believe that further snow storage systems of the Sundsvall type will be built in areas where snow is stored in combination with existing deposits in or close to urban areas.

One major problem with such storage systems is the expensive land cost in densely populated areas. It should therefore be attractive to build such systems in large underground rock caverns.
Underground snow storage/deposits could be located in the city center since it is not occupying expensive land areas.

This means reduce snow transportation and that the snow storage is located where the cooling demand is. Such storage systems need no thermal insulation.

4. Borehole Thermal Energy Storage (BTES)

Borehole systems are the most commonly used ground coupled technology for heating and/or cooling of buildings. A rough estimation is that there are about two million small scale systems for single-family houses. These consist usually of one borehole drilled to 60-200m. Such systems are "always" connected to a heat pump.

The idea of using the ground as a heat source for heat pumps is old. Evans (1805) suggested and described the "Fluid Compression-Expansion Cycle". This method was developed and patented and the first working heat pump was taken into operation in 1835. William Thomson, who later became Lord Kelvin, suggested this system for heating of buildings. As many times before in history the theoretical explanation came long after the invention itself and the heat pump principle was not scientifically explained until 1870. (**Midttømme et.al. 2008)**

The development was slow for many years. In 1910 there was a HP system cooling built in Los Angeles and more systems were built in US in the 1950ies.

The more recent development started at the late 1970ies. In 1977 a 42 boreholes BTES was constructed in Sigtuna, Sweden. This solar heated low temperature seasonal storage system, partly integrated into the building itself, was made for a larger single-family house.

The first large scale high temperature BTES was built at Luleå University of Technology, in 1982. Its 120 boreholes were drilled through 120,000 m^3 of crystalline rock. The storage was heated by waste heat from the local steel plant and coke plant was pumped to the storage via the district heating net **(Nordell, 1994).**

The very first annex within the ECES IA was titled "Large Scale Thermal Storage Systems Evaluation". It meant a technical and economic evaluation of various storage concepts presented by the participating countries; Switzerland (OpA), Belgium, CEC, Denmark, Germany, Sweden, and the USA. The final report was published in October 1981. Results of this work formed the basis for subsequent ECES projects. **IEA ECES IA, 2012)**

Table 1. Stock Conferences 1981-2012

No	Year	Conference Name	Location	Country
1	1981	Seasonal Thermal Energy Storage and CAES	Seattle	USA
2	1983	Subsurface Heat Storage in Theory and Practice	Stockholm	Sweden
3	1985	ENERSTOCK	Toronto	Canada
4	1988	JIGASTOCK	Versailles	France
5	1991	THERMASTOCK	Scheveningen	The Netherlands
6	1994	CALORSTOCK	Espoo	Finland
7	1997	MEGASTOCK	Sapporo	Japan
8	2000	TERRASTOCK	Stuttgart	Germany
9	2003	FUTURESTOCK	Warsaw	Poland
10	2006	ECOSTOCK	Pomona, N.J.	USA
11	2009	EFFSTOCK	Stockholm	Sweden
12	2012	INNOSTOCK	Lleida	Spain

Thermal response testing as a way to obtain site specific thermal properties of the ground was suggested at the second conference, in Stockholm 1983 (Mogensen, 1983). This is further discussed in section 4.1. These conferences boosted international collaboration as indicated by the growing number of countries participating in the annexes. (Nordell, Gehlin, 2009)

Two annexes of vital importance of the BTES development was Annex 8 “Implementing Underground Thermal Energy Storage Systems” and Annex 12 “High-Temperature Underground Thermal Energy Storage”.

Annex 8 which started in May 1994 consisted (at the end) of eight participating countries and several more countries that took part as “observers”. This meant that they could not get funding in their home countries but were interested enough to make it to the meetings. Annex 12 was focusing on HT UTES and I believe that its basic ideas are the way to go for the future. We will have storage systems without any heat pumps for the extraction of heat. This is best achieved by large HT storage systems. Low temperature distribution of heat for space heating is another way to reach this goal.

During the years to come we saw a strong increase in BTES for single-family houses and today there about 2 million systems in the world. In Sweden, which is a very cold and sparsely populated country such small systems supply 15% of all heating (15 TWh out of 100 TWh). Today we have also a couple of thousand larger BTES systems. These ground coupled heat pump systems supply both heating and cooling for commercial and residential buildings.

4.1 Thermal Response Test (TRT)

The first mobile TRT equipment was designed in 1995 at Luleå University of Technology (LTU). It was later constructed and developed within a MSc work at LTU **(Eklöf, Gehlin, 1996)**. The formal MSc seminar was held for the UTES experts at the Annex 8 Experts’ meeting in Halifax, Canada, in June 1996. Their interest for this new measurement method is in my opinion the major reason for the rapidly increasing use of TRT around the world. It resulted in several MSc and PhD thesis on TRT e.g. **Gehlin (2002), Gustafsson (2010) and Liebel (2012).**

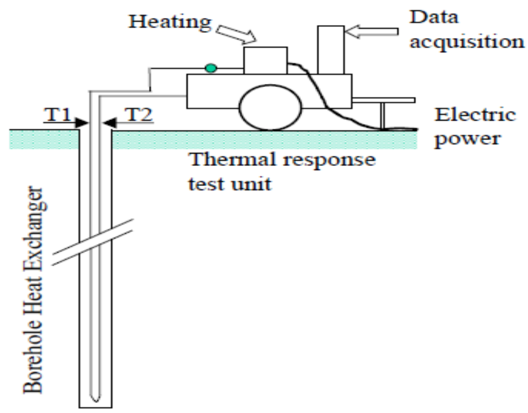
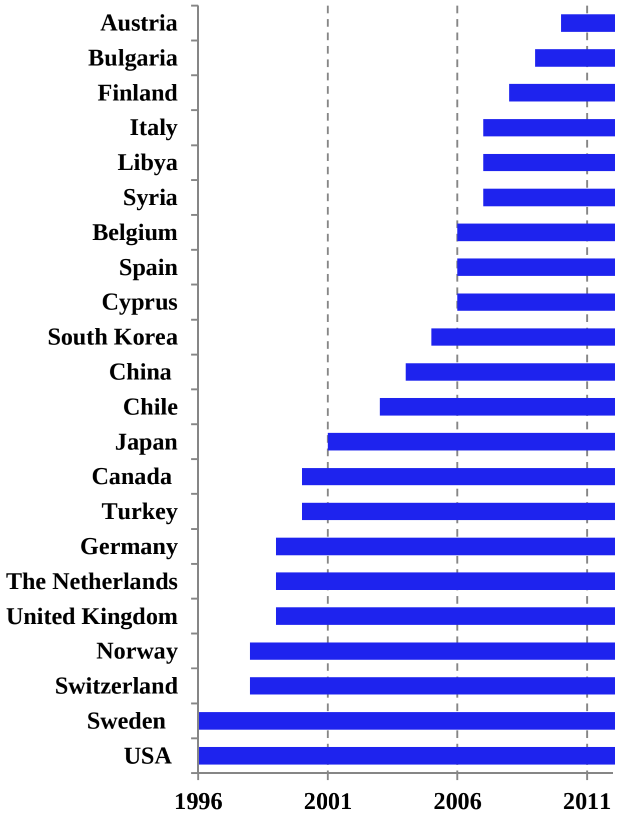


Fig.6 Thermal response test set-up (Gehlin, 2002).

The interest in this technology was indicated by the fact that Gehlins' thesis, some years ago, had been downloaded more than 100,000 times.

TRT became the door opener for BTES systems and thus one important reason for the rapid expansion of BTES systems. Evaluated thermal properties are useful but the main reason for its success, I believe, is the pedagogical principle of this method.

Statistics from various countries statistics on where, how and for what the TRT is used have been compiled in the TRT state-of-the-art report of Annex 21 "Thermal Response Test" (Nordell, 2012). Though it was rather difficult to obtain data from several TRT countries it is estimated that TRT is used in 30-40 countries. Most of the early TRT equipment was built on trailers or in containers.



5. The Stock Conferences

After some years with the ATES/STES Newsletter, at the end of the 1970ies, there was an increasing interest in the field. The first international conference on Seasonal Thermal Energy Storage was held in Seattle in 1981 under the title Seasonal Thermal Energy Storage and Compressed Air Energy Storage, see Table 1. This conference was the start of what late became the "Stock" Conferences.

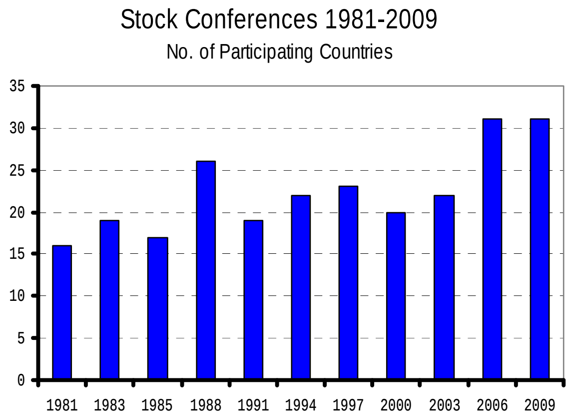
At the Effstock conference in Stockholm 2009, **Nordell, Gehlin (2009)** summarized statistics of the stock conferences since its start in 1981. This gives a pretty good view of how UTES has developed over the years

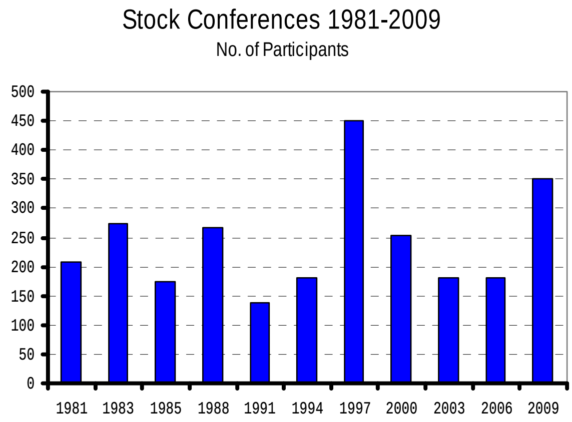
The host country always had a large number of participants. Japan, Germany and Sweden have contributed with most participants. Sweden sent big delegations during the early conferences; Japan has the strongest group during several conferences while Germany sent most participants during the last two years. Spain had the third largest group of participants at the Effstock Conference in 2009 and their interest was further underlined by their interest to host the Innostock conference in 2012.

Table 2. Dominating Countries in Participants, 1997-2009

	Megastock	Terrastock	Futurestock	Ecostock	Effstock	Innostock
1	Japan*	Japan	Japan	Germany	Germany	
2	Sweden	Germany*	Poland*	Japan	Sweden*	
3	Germany	Sweden	Germany	USA*	Spain	

*/ host country





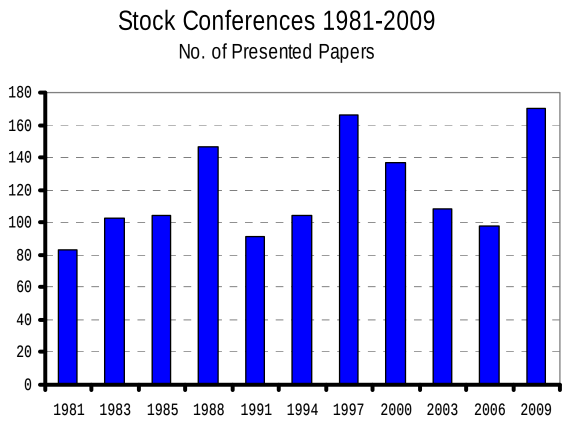


Fig.2 Number of participating countries, participants and presented papers at the Stock Conferences 1983-2009.

6. Conclusions

ATES

I cannot see any fundamentally new ideas of how ATES systems are used. There are some ideas at IKEA in Russia to combine ATES with snow handling (melting) and this way cool the ATES in the winter time.

The number of ATES systems will continue to increase. Accumulated experience of successful operation and also failures will slowly refine the design of such systems. The expansion of such system will continue in suitable geologies in the countries where it already exists and ATES will most likely also spread to other regions with suitable geology.

CTES

We should not expect new CTES systems to be built unless that there are old caverns available. It will be too expensive for as long we can see.

Snow storage

It is hard to convince companies in cold climate that snow and ice are valuable resources for cooling during the summer season. Still it is too good not to be used. Maybe the main barrier is aesthetics – melting snow dumps do not look nice. For that and other reasons I believe that the future for seasonal snow storage/snow deposits is to build underground rock cavern in the center of the cities. This would save money on snow handling and cooling.

BTES

The already large number of BTES systems will continue to increase. Some saturation, though the annual increase is ~10%, is seen in countries like Sweden where at ~20% of all single family houses have BTES for heating. The expansion is much greater in neighboring countries where the use of BTES systems started later.

The growth is in the larger BTES (GSHP) system i.e. that the number of boreholes varies from a few to a few hundreds. In such systems heat pumps are used for heat extraction while cooling is partly done as free cooling at the beginning of the cooling season.

We should expect that the BTES development into new regions will go hand in hand with the TRT expansion. This beauty of this technology is also a barrier. The small scale BTES systems are very simple and once a few storage systems have been made in a new country they are ready to do most of the work themselves.

There is also an increasing interest to store heat for single family houses, to cover the annual heat demand. This will always be attractive but it is a difficult task. Recent visions are connecting such very high temperature storage systems (~1000°C) with an intermittent heat source that will be available also during the winter. The high temperature and also the possibility to inject heat also during the winter reduce the required storage volume.

There is an increasing interest for high temperature heat storage. The idea is to store waste heat and solar heat and recover stored heat without heat pumps. To achieve this, storage volumes are getting bigger and/or the heat is distributed at lower temperature (floor heating or other low temperature applications). There is one good example in Sweden, the Emmaboda BTES system in which 3.8 GWh of HT industrial waste cvheat is stored during the summer season and 2.6 GWh is recovered during the heating season. The injection temperature is usually 60°C but part of the heat is injected to at 70°C. Heat injection started during the summer of 2010 (Andersson, 2012).

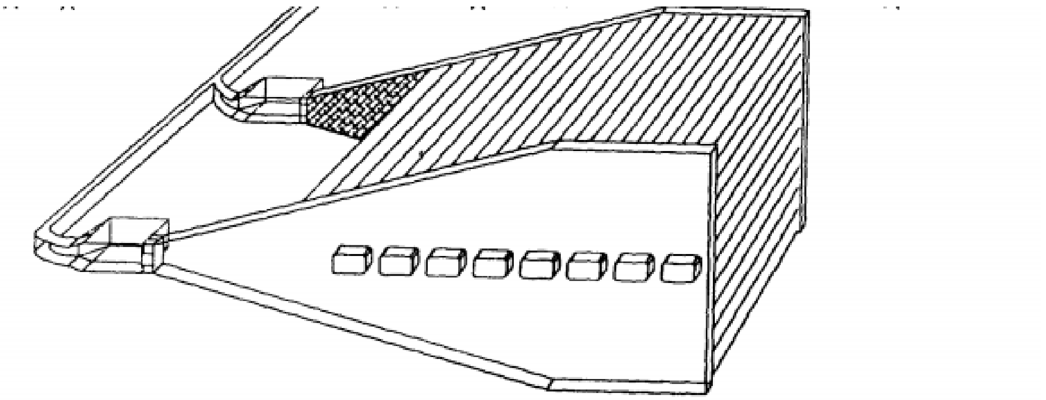


Fig.8. BTES/CTES combination heat store.

Another, rather secret, development is on and old heat storage idea which combines the BTES and the CTES systems (**Nordell B. et.al., 1994).** The meaning is to get the advantage of the great heat injection/extraction power of the CTES and the much lower cost of the BTES. This system is meant to be huge (20-100 GWh) and operated without heat pumps.

7. Acknowledgements

Since this is my 12th and last Stock Conference I will take the opportunity to thank all friends and colleagues in the field of underground thermal energy storage during the last 30+ years.

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