Large-scale Thermal Energy Storage

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ABSTRACT

Renewable thermal energy is usually available when the energy demand is low. This mismatch can be balanced by seasonal storage of energy in Underground Thermal Energy Storage (UTES) systems. The most common technologies are aquifer storage (ATES), borehole storage (BTES) and rock cavern storage (CTES). It is not possible, for geological or geo-hydrological reasons, to construct all these systems at any location but one of them can in most cases be realised. ATES is most favourable in large-scale applications, BTES is the most general system because it has applications in all scales. CTES are most favourable when loading/unloading powers are strongly varying or extremely high. This paper gives a brief summary of seasonal thermal storage technologies and its necessity for the large-scale utilisation of renewables.

BACKGROUND

Renewable energy is solar energy one way or the other. The most obvious renewable energy source is solar radiation but it also occurs as wind energy, wave energy, and as thermal energy passively stored in air, water, or in the ground. Solar energy is also stored in plants and trees. Renewable energy is defined by its time of renewal. So, bio-fuel is a renewable energy but oil is not because it takes such a long time for its renewal. Because of low intensity or absence of solar energy snow and ice are accumulated during the winter. This type of natural cold storage is also a type of renewable energy or rather a shortage of heat that can be used in cooling applications.

This paper deals with thermal energy only, which leaves us with the following renewable energy resources:

- Solar Energy Resources
- Biomass Energy Resources
- Geothermal Energy Resources?
- Snow/Ice Energy Resources

In most climates there is a time difference between supply and demand of renewable energy. This mismatch can be solved by energy storage. There are many technologies developed for short-term and long-term storage. In this paper seasonal storage of thermal energy is discussed. Thermal energy storage systems can be classified according to:

- Storage Purpose - Heating, cooling or combined heating or cooling
- Storage Temperature - Low < 40-50^{o}C and High >50^{o}C
- Storage Time – Short term (hours- weeks) or Long term (months - seasons)
- Storage Technology - ATES, BTES, CTES, DTES, Pit/Tank Storage, PCMES
- Storage Application - Residential, Commercial or Industrial

Energy Storage History

Man has used passively stored energy throughout history. Early examples are people who lived in natural or excavated caverns in rocks and soils. Such dwellings were warm in the winter and cold in the summer because the seasonal temperature variation does not penetrate deeply into the ground. It is also known that the buildings of the native people of Arizona and New Mexico worked in the same way but on a diurnal basis. In this case the heat of the day did not penetrate the wall until the coldest hour of the night while the cold of the night was cooling the inner wall surface during the warmest period of the day. There are also many examples of ice cellars where ice was stored from the winter for cooling purposes during the summer.

Small-scale short-term storage of hot water and ice was early made in warm water bottles. Another example is electric water heaters in single family houses. Such heaters are motivated by power saving meaning that the heater takes many hours to produce necessary hot water while the hot water is used during shorter periods of the day.

One of the earliest types of technical energy stores were large water tanks to reduce the peak power demand. Such stores are now common in District Heating systems and also in solar applications. Storage systems are also needed in solar applications because of the diurnal variation in solar intensity. In this way solar energy is available after sunset. The variation in solar intensity also results in the need of weekly and seasonal storage.

The interest in large-scale seasonal thermal energy storage started with the oil crisis in the early seventies. At the beginning of seasonal storage research the long-term aim was to store solar heat from the summer to the winter primarily for space heating. Industrial waste heat was another heat source of great potential. This is still true but in recent years cooling has become an increasingly important issue and District Cooling (DC) systems are growing in Europe. So far, these systems have utilised passively stored cold but now we see an increasing interest in large-scale seasonal cold storage systems.

There are other advantages of energy storage e.g. this technology is benign to the environment. This is, however, not a good enough reason, as long as the environmental advantages have not been given an economical value. Sometimes we find that storage systems are built for political or environmental reasons. In such cases e.g. companies want to have an environmental image and for that reason decide to invest in a storage system but then the company has given this image an economical value.

The only valid reason for energy storage in a market economy (like it or not) is that it is more cost effective to store energy from one time to another, than to produce it later when needed. This implies that the storage energy must be cheaper when injected than the value of energy when it is recovered. This price difference must be big enough to cover the cost of investment, maintenance, operation, and energy losses. Today, there are many economically feasible storage applications.

SEASONAL THERMAL ENERGY STORAGE

Storage of sensible heat results in an energy loss during the storage time. This loss is a function of storage time, storage temperature, storage volume, storage geometry, and thermal properties of the storage medium. Since seasonal thermal energy storage requires large inexpensive storage volumes the most promising technologies were found underground in Underground Thermal Energy Storage (UTES) systems. The most common UTES technologies are Aquifer Thermal Energy Storage (ATES), Borehole Thermal Energy Storage (BTES), Rock Cavern Thermal Energy Storage (CTES).

ATES - Aquifer Thermal Energy Storage

In ATES systems thermal energy is stored in the ground water and the minerals of an aquifer. One or more wells are drilled for injection and extraction of groundwater, which is the heat carrier of the ATES system (Figure 1). For ATES two concepts are possible:

- Alternating flow for loading and unloading the store, thus switching the production and injection wells and creating "warm" wells and "cold" wells.
- Continuous flow in one direction, with varying temperatures at the injection well and mean temperatures at the production well. This is used for cooling applications.

ATES systems are used for short term and long term storage. The greatest number of ATES were built in China in the 60'ies. In recent years a large number of systems were built in the Netherlands and Sweden. ATES is economically feasible in a lot of applications. (Bakema et.al. 1995 and 1998).

There are two major problems when considering an ATES system.

- Conflicts of interest in ground water use
- Water chemistry

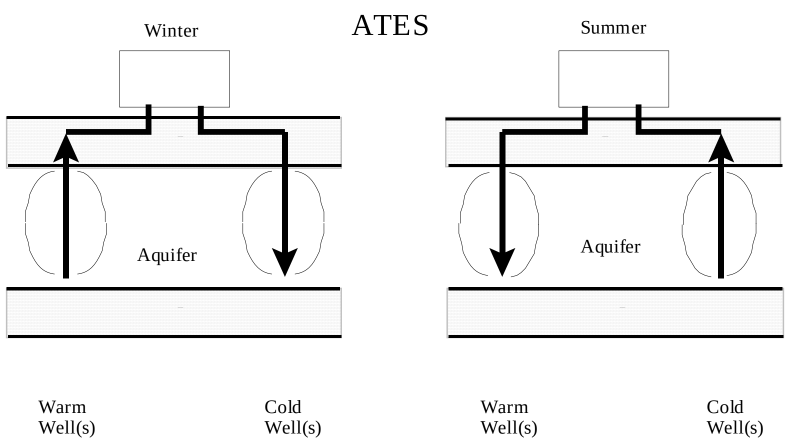

Figure 1. Outline (section) of an ATES System. The flow direction is reversed during the summer and the winter to get the highest

There are a number of computer models to design and simulate the thermal behaviour of ATES system for different loads geological conditions. The best groups for designing and simulating ATES are found in the Netherlands, Sweden and USA.

BTES - Borehole Thermal Energy Storage

Borehole systems (BTES) are the most generally applicable UTES. In such systems bedrock is used as the storage medium. The boreholes that penetrate the storage volume are heat exchangers of the system, through which a heat carrier is pumped. A pipe system is installed in the borehole to enable the circulation of a heat carrier. When thermal energy is injected the temperature of the storage medium is increased.

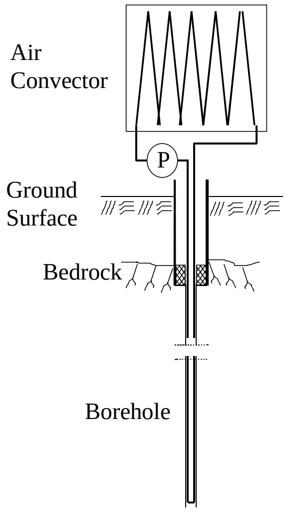

Figure 2. Section through a single borehole system

The BTES system has many applications.

Small-scale systems:

- Single borehole for cooling (with and without recharge)
- Single borehole for heating with heat pump (with and without recharge)
- Single borehole for heating with heat pump and direct cooling

Large-scale systems:

- System of Boreholes for heat extraction with heat pump
- System of Boreholes for heat extraction with heat pump and recharge of extracted energy

Borehole Storage Systems

- Seasonal loading of thermal energy (heat or cold) for later extraction
- Seasonal loading of thermal energy for the purpose of cooling or heating of the ground

BTES systems are most suitable for base load operation, both when loading and unloading the store. It is mainly for seasonal storage. The theory of BTES was summarised by Hellström (1991). Most of the models for simulation and design of BTES systems were developed by (Hellström 1987, 1997)

Many hundreds of thousands of BTES systems have been constructed around the world. The Geothermal Heat Pump Consortium (GHPC, see WWW Ref. GHPC) estimates that 400.000 BTES systems would annually be built in US within a few years. Most of them are borehole systems of one or a few boreholes. There are however an increasing number of large-scale systems i.e. more than 10-20 boreholes.

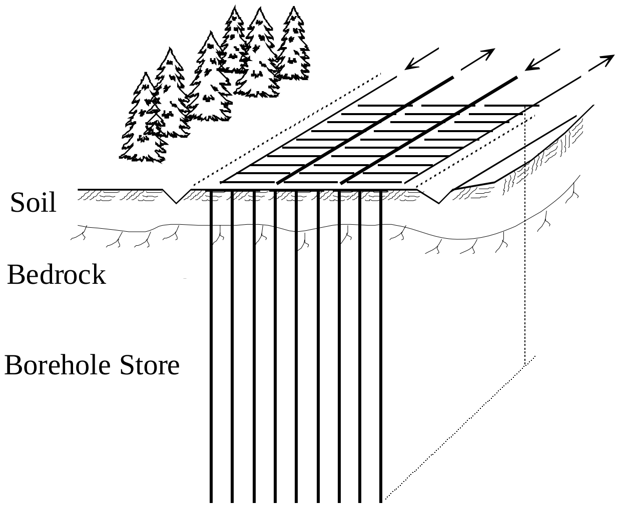

Figure 3. Section through a borehole system. The construction of this high temperature solar heated seasonal store started in February 2000 in Anneberg, Stockholm. The store consists of 99 boreholes (c/c 3 m) drilled to a depth of 65 m in granite. This is a high temperature store for low temperature space heating of buildings. (After Nordell, Hellström, 1999).

BTES systems are most favourable for direct cooling i.e. without heat pumps, even though heat pumps sometimes are required. Another type is a high temperature store delivering heat for low temperature heating. Only a few high temperature BTES have been built since the first large-scale high temperature BTES at Luleå University, Sweden, in 1982 (Nordell, 1994).

A good application of high temperature storage for a low temperature application is now being studied at Luleå University of Technology. A high temperature BTES, loaded with waste heat during the summer, will be used for de-icing of the airport runways during the winter. The runways are de-iced by hot water circulation in a plastic pipe system embedded in the paved runways. Several similar BTES are in operation in Japan for de-icing of paved areas (Iwamoto et.al. 1998). In the SERSO project in Switzerland the paved area is also used as a solar collector during the summer, which delivers the heat for charging the BTES.

Another interesting application suggested (but never tested) is a backup storage for industrial waste heat utilised in a DH system. The problem to solve is that when industrial waste heat is used for heating of larger districts there must be some kind of backup heat supply for standstill periods, for repair and maintenance, at the industry. So, the store would be continuously loaded, like a battery backup, and unloaded only if there is a need for it. The size of the storage must be decided from the possible standstill periods. Such systems would enable an extended utilisation of waste heat.

When BTES is constructed in soils or clays it is usually called Duct Thermal Energy Storage (DTES). There are many such plants constructed in Europe - with horizontal or vertical plastic pipes in the ground. Some of them are operating at high temperatures but most of them are connected to heat pumps and thus operating close to the undisturbed ground temperature.

CTES - Rock Cavern Thermal Energy Storage

In the Rock Cavern Thermal Energy Store (CTES) energy is stored as hot water in an underground cavern. In such a system with a large volume of water it is of great importance to maintain a stratified temperature profile in the cavern. During injection hot water is injected at the top of the store while colder water is extracted from the bottom.

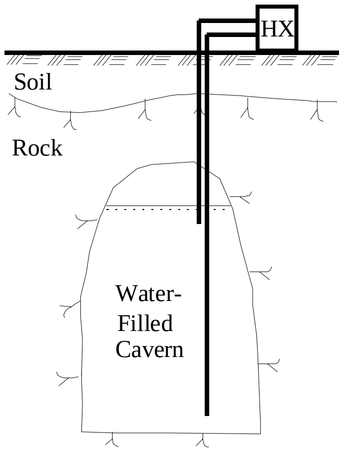

Figure 4. CTES - Rock Cavern hot water storage.

Two such storage systems were built in Sweden, Avesta with a volume of 15,000 m^3 and Lyckebo with a storage volume of 115,000 m^3. The Avesta CTES was built in 1981 for short-term storage of heat produced at an incineration plant. The Lyckebo store, which is partly heated by solar energy, has been in operation since 1983. There are a few more CTES systems built but in these cases the caverns used were not initially constructed for CTES. There are examples of shut down mines and oil storage caverns that have been reconstructed for hot water storage. (Gustafson G, 1985)

Rock caverns are very expensive to construct. CTES still have a big advantage - the powers of injection and extraction are very high. So, CTES can be used to meet very high powers.

It is also possible to use CTES as part of a system for ice/snow storage, see PCMES.

PCMES - Phase Change Material Energy Storage

Phase Change Material (PCM) melts and takes up energy corresponding to the latent heat (heat of fusion) of the material when its temperature is increased. When it is getting cooler the PCM solidifies and heat is released. For cooling purposes there will be a reversed process. (Alexandersson K., et.al 1996)

There are several types of PCM used for energy storage e.g. paraffin and water (ice). Such storage systems have high storage density. Other qualities of PCM systems are that there is no thermal loss from the storage medium and that the latent heat (when recovered) is obtained at a constant temperature i.e. at the melting point of PCM.

Paraffin has one big advantage; it is possible to select an appropriate working temperature or melting point of the paraffin at least in the range of -30^{o}C to 115^{o}C. The heat of fusion (latent heat) for such paraffins are about half that of water, i.e. approximately 200 kJ/kg. Consequently, there is paraffin for many different applications. Such systems are now being developed within the IEA, see International Collaboration below. One problem with these materials is that the high cost of e.g. paraffin.

For large-scale energy storage applications ice is the most common PCM. Because of the low melting point of ice such systems are mainly used in cooling applications. The historically old technique of ice storage, using sawdust as thermal insulation, is now being rediscovered. There are several seasonal snow/ice storage systems in e.g. Japan and Canada (Skogsberg, 1999).

The first "modern" large-scale seasonal snow storage in Sweden is now being constructed. The snow deposit of the city of Sundsvall will be used for cooling of a hospital during the summer (cooling demand 1000 MWh, peak power 1.5 MW).

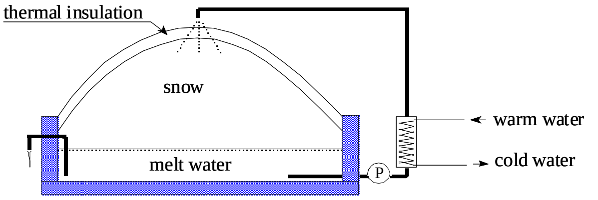

Figure 5. Principle of the snow deposit seasonal cold storage.

The snow deposit contains about 20.000 tons (30.000 m^3) or roughly 2000 MWh of cooling energy (latent heat). Calculations show that by using 0.1 m of wood chips as thermal insulation 70% of the snow will last over the summer. Wood chips are used in the heating plant of the District Heating system, so after one summer of cooling the hospital the used wood chips will be burnt. The snow is stored on a watertight floor with a surrounding vertical wall. Thus the melt water is contained under the snow surface. The melted water, with a constant temperature of 0^{o}C, is pumped through a heat exchanger connected to the cooling system of the hospital and re-circulated to the snow deposit (Figure 5).

A similar application, a combined CTES as snow deposit and seasonal cold storage was recently investigated at LTU (Johansson,1999). It was shown that even if the cost of the cavern is very high, 500 SEK/m^3 (~60 USD/m^3), the pay-off time for such a system would be about one year for a 100,000 m^3 rock cavern. Furthermore this store would mean that the snow does not have to be transported away from the city which means savings in both transportation and environment. See Figure 6.

For all these UTES system one of the most important external factors is the required temperature level for the heating/cooling case involved. Thermal energy storage systems become more efficient if the temperature requirement for space heating is low, about 35^{o}C and if the temperature for cooling is about 15^{o}C, i.e. a temperature difference of 10^{o}C. This also explains why high temperature storage and low temperature applications are most favourable.

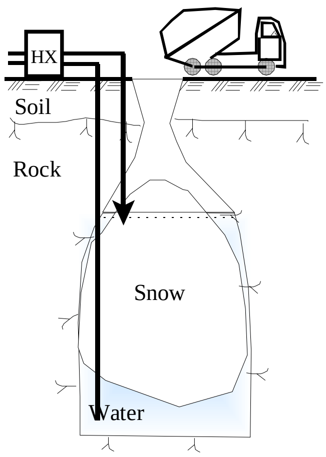

Figure 6. Rock cavern for seasonal snow storage.

INTERNATIONAL COLLABORATION

A series of international conferences in the field of Underground Thermal Energy Storage started in Seattle, USA, 1981. The next (8^{th}) international conference, TERRASTOCK, will be held in Stuttgart, Germany, in 2000. These conferences gather about 200-300 scientists, experts and decision-makers from 25 countries. Another form of international collaboration is carried out within the framework of the International Energy Agency (IEA). One program is Energy Conservation through Energy Storage, which organises several research projects on different storage technologies. Here the project Implementing Underground Thermal Energy Storage Systems 8 is briefly described.

The scope is to conserve energy and to improve the environment by facilitating an extended use of UTES in the building, industrial, agricultural and aqua-culture sectors. Annex 8 disseminates UTES information on different levels depending on the target group.

1. General Information. Philosophy, UTES Potential, benefits, system. Target Group: Politicians, Decision makers
2. Engineering Information. Demonstration projects, Systems and applications, Design Tools. Target Group: Architects, Consulting Engineers, and Public Works on community level
3. Scientific Information. Theory, Teaching, Courses, Books, Detailed modelling. Target Group: Scientist, students, post graduate students

The means employed to achieve the objectives are collaborative efforts based upon co-operation and task. Nine countries (Belgium, Canada, Germany, Netherlands, Poland, Sweden, Turkey, USA, and Japan) represented by their UTES experts are involved in this work. New participating countries (with little experience of UTES) start to perform national potential studies but are also participating in ongoing work.

There have seen a strong UTES development in the participating countries. One recent result of the Annex 8 work was the start of Underground Thermal Storage and Utilization - A Peer Review International Journal on Energy Conservation. It is an electronic journal [WWW Ref. UTSU]. Further information about IEA, ECES IA and Annex 8, see [WWW Ref. ECES].

Since several of the participating countries have found the Annex 8 work rewarding, a new similar annex will be started when the ongoing work is terminated in 1999. Then also new participants are expected to join.

CONCLUDING REMARKS

- ATES systems are feasible when the geological conditions are favourable. ATES is for large-scale cooling or heating. Still it is used for both short-term and seasonal cold and heat storage. ATES is a standard option in some countries.
- BTES is the most general type of UTES system. It is feasible in a very small scale and also in large scale. The soil cover should however not be too deep. BTES is most efficient when the task is to load and unload a base load of thermal energy. Because of the pipe installations it is possible operate at below freezing degrees.
- A combination of CTES and PCM, i.e. seasonal storage of ice and snow in a rock cavern for district cooling seems to be very promising application.
- The most important external factor for efficient UTES systems is that the temperature requirement for space heating is low, about 35^{o}C and that the temperature requirement for cooling is about 15^{o}C, i.e. a temperature difference of 10^{o}C.
- The most favourable UTES applications are high temperature storage with low temperature applications without heat pumps.
- The long-term aim of storing solar heat from the summer for space heating during the winter does not seem to be far away. The Anneberg project was the first Swedish solar energy - seasonal storage project that showed similar cost for both the solar system and best conventional alternative.
- International Energy Agency results in efficient international collaboration and technology transfer. There are several ongoing projects on renewable energy and energy storage.
- The newly started Underground Thermal Storage and Utilisation - An International Peer Review Journal on Energy Conservation - has the potential to become an important forum for scientific and technical UTES information.

UTES conserves energy and improves the environment. There are many applications found in e.g. the building, industrial, agricultural and aqua-culture sectors. One big advantage for the widespread use of UTES is that local entrepreneurs are able to carry out the construction work (for BTES in particular). It should be utilised in many more countries throughout the world. Renewable energy has a great potential. Our future energy system must be based on renewable energy, an energy system in pace with Nature – without it there is no future. The key to success is international collaboration, then UTES and renewable energy will make the future come sooner.

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[http://www.sb.luth.se/vatten/projects/iea/]

GHPC - Geothermal Heat Pump Consortium.
[http://www.ghpc.org/]

UTSU - Underground Thermal Storage and Utilization.
[http://www.geo-journal.stockton.edu/]