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Heat and Cold Energy Storage Technologies as a Practical Complement to Renewable Energy Installations

Abstract
Thermal energy storage can be defined as temporary storage of heat energy at low or high temperatures. The development and innovative solutions of the thermal energy storage technology can, in the long-term, mitigate the negative impact on the environment and facilitate more energy-efficient exploitation of thermal energy systems. The main goal in thermal energy storage systems is to store the solar heat accumulated during the summer for heating in winter. The concept of such use of solar energy is not new, because it has already been developed and improved over the centuries, where it has played an important role in energy saving and significantly contributed to the improvement of energy efficiency and reduction of gas emissions to the atmosphere. The article presents the types of heat storages with particular emphasis on BTESstorage systems with examples of their applications.
Keywords: energy storage, types of heat storage, heat storage loading and unloading, energy efficiency, heat pumps.

1. Introduction

The energy needs of society are constantly growing especially in large urban agglomerations, while fossil fuel resources, which are an energy product for the majority of national energy and heating systems, are running out. One can see that the price of traditional fuels (gas, oil, coal) will irreversibly undergo a year-to-year increase (Abedin, & Rosen, 2011). Advanced technologies of short-term and long-term thermal energy storage can significantly reduce environmental problems (the effect of reducing CO_2 emissions) and increase the efficiency of heating and cooling systems. The simplest solution that increases the energy efficiency of heating and cooling installations is the use of Thermal Energy Storage (TES).

TES is defined as the temporary storage of thermal energy in the form of hot as well as cold medium for later use. The dependence of the use of renewable energy technologies plays a significant role in the process of thermal energy storage. The creation of hybrid energy storage systems supported by renewable energy systems is aimed at optimal utilization of the efficiency potential of heating systems and minimizing energy shortages with simultaneous storage of excess heat for later use in peak periods. TES technologies are advisable for balancing the demand and supply in the thermal energy market. Therefore, we can say that TES plays an important role in increasing the energy efficiency of individual types of renewable energy in the energy mix on a micro and macro scale (Abedin, & Rosen, 2011). The choice of a TES system for a specific application depends on many factors, including the duration of storage, economy, supply and use of temperature, capacity, heat loss and space availability requirements (Abedin, & Rosen, 2011).

Seasonal Thermal Energy Storage (STES) in a nutshell are systems designed to accumulate excess solar or waste energy in the summer and store it with a target application in mind in winter and transitional periods. The heat and cold energy storage requires large capacities and its proper functioning depends on many technical parameters. However, energy storage engineering technology is constantly being improved and modified in order to find optimal solutions. Well-designed STES systems increase the initial investment costs but significantly reduce the maintenance, heating and cooling energy costs during operation, which amounts to improving the energy efficiency of heating systems. The most cost-effective STES projects are projects that take into account the year-long cyclic process (loading and unloading) of energy surpluses in combination with hybrid energy generation systems (Pavlov, & Olesen, 2011a; 2011b). The larger the system, the more energy-efficient as well as the GJ price of thermal energy becomes more profitable for the end customer.

To sum up the previous considerations, we can distinguish five types of basic solutions in the seasonal thermal energy storage (STES) technology:
– Tank Thermal Energy Storage (TTES),
– Pit Thermal Energy Storage (PTES),
– Borehole Thermal Energy Storage (BTES),
– Aquifer Thermal Energy Storage (ATES),
– Cavity Thermal Energy Storage (CTES).

In the further part of the article, an analysis of particular types of seasonal energy storage systems will be carried out, with particular reference to BTES storage with examples of its applications.

2. Tank Thermal Energy Storage

Tank Thermal Energy Storage is a structural solution with a traditional circular shape. The tank is built from scratch, usually with a reinforced concrete or steel structure, thermally insulated, closed with a sealed overlay, with the supply and discharge of the heating medium. In the final stage, the entire TTES is covered with a layer of soil to protect individual layers of the tank.

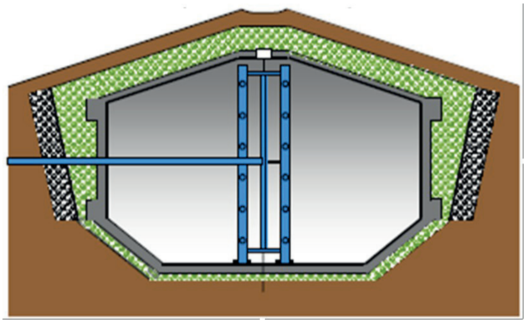

Fig. 1. General structure cross section of the TTES energy storage with a visible insulating layer around the tank. The efficiency of this type of tanks is determined at a level of 60 to 80 kWh/m^3

Source: *State of the Art of Thermal Energy Storage Solutions in Buildings*, Master's thesis, C. Sunliang, 2010, Jyväskylä: University of Jyväskylä, Finland.

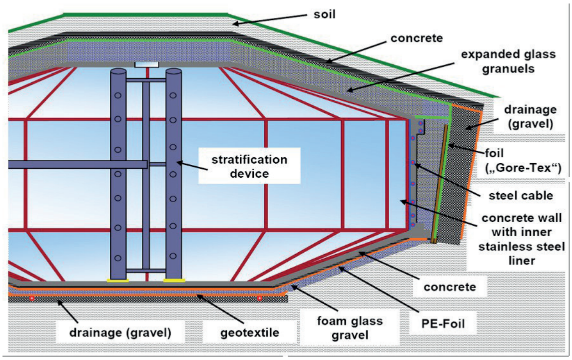

Fig. 2. Cross-section of the TTES energy storage system with constructional details of tank layers

Source: *State of the Art of Thermal Energy Storage Solutions in Buildings*, Master's thesis, C. Sunliang, 2010, Jyväskylä: University of Jyväskylä, Finland.

3. Pit Thermal Energy Storage

(PTES) is a structural solution with any geometric shape. The systems of this type are built by making an insulated technical pit and covering it tightly with a removable insulating coating, with the supply and discharge of the heating medium as in the case of TTES tanks. The PTES solution does not require special geotechnical conditions, it is economical and easy to make.

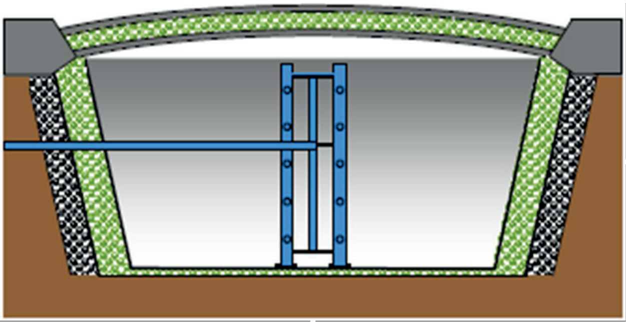

Fig. 3. The general structure cross section of the Pit Thermal Energy Storage with a visible insulating layer around the tank. The efficiency of this type of tanks is determined at a level of 30 to 80 kWh/m^3

Source: *State of the Art of Thermal Energy Storage Solutions in Buildings*, Master's thesis, C. Sunliang, 2010, Jyväskylä: University of Jyväskylä, Finland.

4. Borehole Thermal Energy Storage

Borehole Thermal Energy Storage is a specific type of energy storage. The element that stores thermal energy is the ground. Thermal energy or cooling energy is transferred to the ground by means of vertical probes (vertical ground heat exchanger). Vertical probes are connected with each other in a serial or parallel way in order to obtain an even effect of loading or unloading the storage system (Ercan Ataer, 2006; Pavlov, & Olesen).

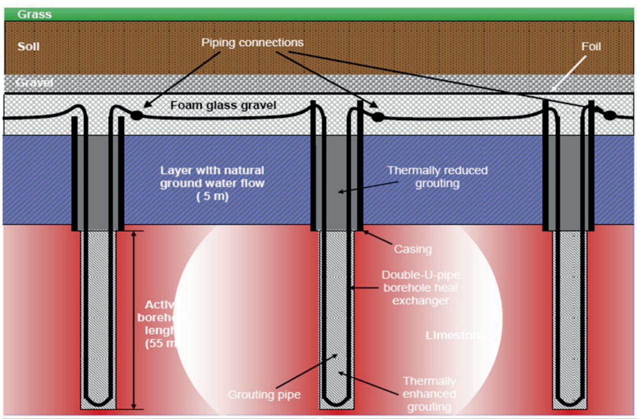

Fig. 4. Borehole Thermal Energy Storage with a system of connections between individual vertical probes

Source: Sustainable Thermal Energy Storage Technologies, part I: Heat Storage Materials and Techniques, S.M. Hasnaina, 1998, *Energy Conversion and Management, 39*, pp. 1127–1138.

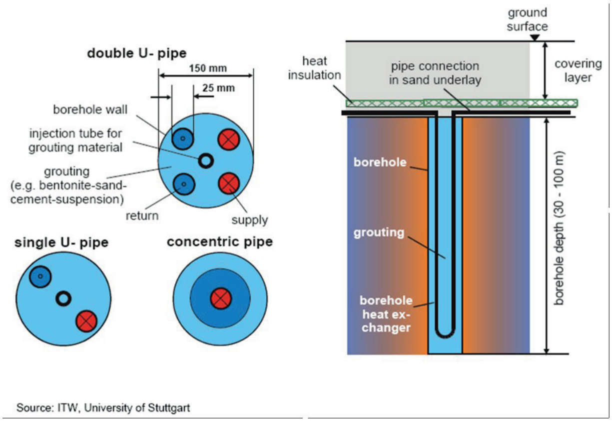

Fig. 5. A cross-section of the Borehole Thermal Energy Storage with construction details of a vertical heat exchanger. An example of construction solutions for vertical probes in three systems: single U-pipe system, "pipe in pipe" concentric system, double U-pipe system

Source: Development of a ground source heat pump system with ground heat exchanger utilizing the cast-in-place concrete pile foundations of buildings, K. Sekine, R. Ooka, S. Hwang, Y. Nam, Y. Shiba, 2007, *Ashrae Transactions, 113*, retrieved from: https://intraweb.stockton.edu/eyos/energy_studies/content/docs/final_papers/11a-3.pdf.

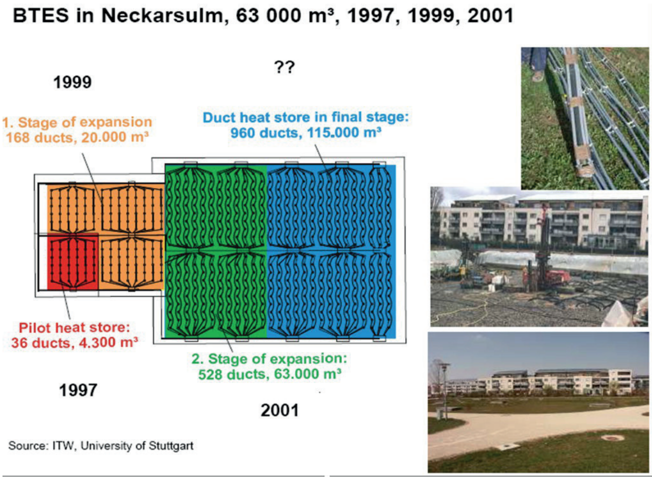

Fig. 6. An example of individual phases of construction of the Borehole Thermal Energy Storage in Neckarslum, Germany, 1997–2001 — installation project

Source: Development of a ground source heat pump system with ground heat exchanger utilizing the cast-in-place concrete pile foundations of buildings, K. Sekine, R. Ooka, S. Hwang, Y. Nam, Y. Shiba, 2007, *Ashrae Transactions, 113*, retrieved from: https://intraweb.stockton.edu/eyos/energy_studies/content/docs/final_papers/11a-3.pdf.

An important computational element in the design and selection of BTES energy storage is the implementation of the numerical simulation with the finite element method. Numerical simulation allows one to determine the temperature fields, heat flow gradients with high accuracy, visualize in the 3D grid the behavior of the temperature field as well as flows in a given period of time. An important element in the parameterization of energy storage is the determination of boundary conditions and the introduction of parameters related to the water flow in the ground layers. Water flows in the ground in energy storage are an unfavorable phenomenon, because the accumulated heat of low exergy is dispersed, which causes uncontrolled heat leakage. In the ground there are phenomena of heat exchange in the form of convection and heat transfer, as shown in the Figure below.

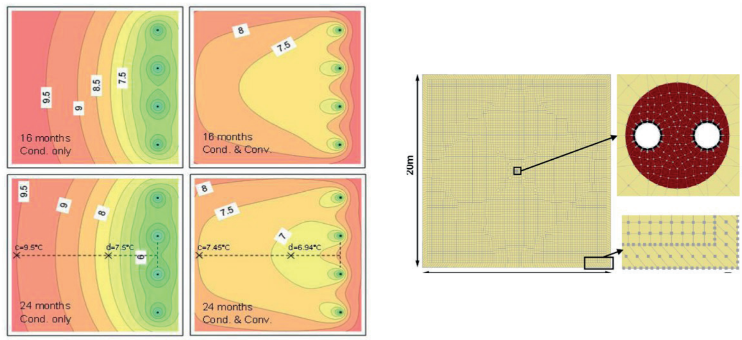

Fig. 7. Numerical simulation of ground energy storage using FEM Finite Element Method) or the CFD Computational Fluid Dynamics) is one of the most effective methods for determining the thermal possibilities of heat and cold energy storage. On the left side, numerical simulation of energy storage and temperature distribution only with conduction and conduction with convection. The effect of convection and unidirectional water flow in the ground causes uneven stretching of the temperature field

Source: Development of a ground source heat pump system with ground heat exchanger utilizing the cast-in-place concrete pile foundations of buildings, K. Sekine, R. Ooka, S. Hwang, Y. Nam, Y. Shiba, 2007, *Ashrae Transactions, 113*, retrieved from: https://intraweb.stockton.edu/eyos/energy_studies/content/docs/final_papers/11a-3.pdf.

5. Aquifer Thermal Energy Storage

Aquifer Thermal Energy Storage is a structural solution that uses natural or artificial aquifers. The implementation of this type of tanks must be preceded by detailed hydrogeological tests, which are designed to eliminate the threat in the form of disruption of flows in aquifers. These systems use the natural temperature capabilities of aquifers and are a factor that increases the efficiency of heating and cooling systems. The chemical composition of such deposits should also be taken into account, as a high content of a salt compound or a high degree of iron content in water may lead to damage to the installation in a short time. For this purpose, heat exchangers and transmission pipelines made of composite materials or of titanium or molybdenum stainless steel should be used (Pavlov, & Olesen).

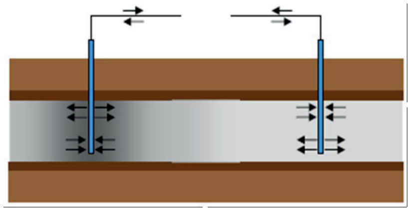

Fig. 8. Aquifer Thermal Energy Storage with a system of connections between aquifers

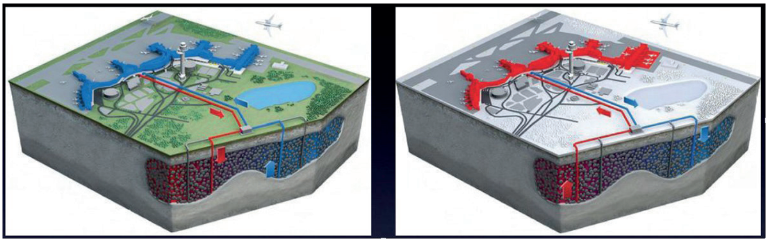

Fig. 9. Example of Aquifer Thermal Energy Storage on the aquifer in Arlanda Airport in Stockholm

Source: PSPC technical and conference materials.

The ATES heat and cold storage system at Arlanda Airport near Stockholm consists of 11 wells, with a water flow of 720 m^3/h. The thermal capacity is about 10 MWh/year (volume of 3 million m^3). The project analysis showed energy savings of 4 GWh/a year of electricity and 10 GWh/a year of heat. In addition, the gravel-water storage at Arlanda Airport has reduced SO_x and NO_x as well as CO_2 emissions. This type of solution is also used to melt the layer of snow and ice in the technical area of the airport.

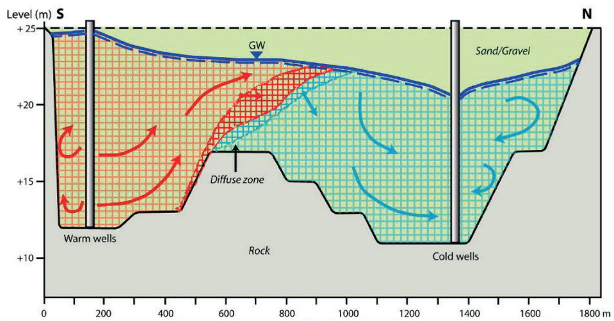

Fig. 10. Cross-section of the ATES energy storage with the temperature stratification shown and the SWECO system for balancing seasonal temperature fluctuations at Arlanda Airport

Source: PSPC technical and conference materials.

Economic summary for ATES energy storage at Arlanda Airport:

– operating cost < 1 Euro/kWh;
– CO_2 emission reduction: 7,000 tons/year;

– investment costs: 5 million Euro;
– investment payback period: 5 years!
– Saved energy:
– heat energy: 25 GWh/year;
– cold energy: 5 GWh/year;
– electricity: 4 GWh/year.

6. Cavity Thermal Energy Storage

Cavity Thermal Energy Storage is a structural solution that uses existing underground excavations. In this way, existing but not used cavities can be used for heating purposes, in which the heating medium can be stored for existing heating systems. Technical adaptation that is cavity sealing is the biggest problem in this type of systems.

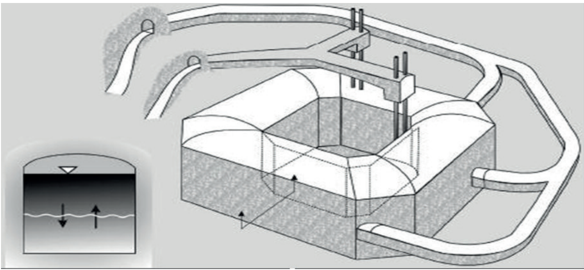

Fig. 11. Cavity Thermal Energy Storage with a system of connections constituting natural tunnels, through which heat energy is supplied and discharged. The storage capacity is about 105,000 m^3

Source: *Thermal energy in buildings storage — concepts and applications*, G. Pavlov, B.W. Olesen, retrieved from: http://www-ttp.particle.uni-karlsruhe.de/GK/Workshop/blobel_maxlik.pdf.

Cavity Thermal Energy Storage (Fig. 11) is intended for providing about 550 single-family houses with heat energy. This storage performs the function of space heating and the demand for hot water, the whole system is additionally supported by the energy from the installation of solar collectors with an area of 4320 m^2. The heating water is transported to the chambers of the storage tank and operated by a system of two telescopic pipelines, which ensures its optimal temperature distribution, i.e. stratification of the temperature field in individual working layers at the level of 90 to 40°C from the top layer to the bottom layer.

7. Conclusions

The review of available methods for seasonal storage of solar energy clearly shows that the use of such solutions for storing energy in the form of sensible heat contributes on a long-term basis to effective reduction of fossil fuel consumption needed for thermal energy production, which is in line with EU guidelines on CO emission reduction$_2$ in the member states but also around the world. In addition, an important factor is the economy, where for large investments the payback period is 5–8 years.

In most EU states, the use of the ground for thermal energy storage must be approved by the implementation of an appropriate technical design together with a positive opinion issued by the relevant environmental authorities. The decision to build a specific type of energy storage depends mainly on local, geological and hydrogeological conditions. In Polish conditions, BTES (Borhole Thermal Energy Storage) solutions, i.e. a vertical ground heat exchanger, are most often used. This type of solution, due to the similarity in the workmanship, is often confused with the ground source heat pump. The technical differences between the BTES storage and the ground source (vertical probes) to supply the heat pump system result from the nature of the operation of these systems. Ignorance of the principles of BTES energy storage design can lead to operating problems as well as, in the long term, the energy failure.

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