Life Cycle Analysis of Underground Thermal Energy Storage

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Abstract
Underground Thermal Energy Storage (UTES) systems are used to buffer the seasonal difference between heat and cold supply and demand and, therefore, represent an interesting option to conserve energy. Even though UTES are considered environmental friendly solutions they are not completely free of impacts on the environment in general and the subsurface in particular. In order to improve the understanding and knowledge on the environmental performance of UTES techniques, this study performed a Life Cycle Assessment (LCA) on two different UTES systems: Aquifer Thermal Energy Storage (ATES) and Borehole Thermal Energy Storage (BTES).

Keywords
Aquifer thermal energy storage • Life cycle assessment • Efficiency • Sustainability

232.1 Introduction

Underground Thermal Energy Storage (UTES) systems are used to buffer the often seasonal difference between heat and cold supply and demand and, therefore, represent an interesting alternative to conserve energy. Furthermore, UTES systems can be coupled with renewable energy production systems like solar thermal collectors. As stated in the IEA strategic plan (2011–2015): "*energy storage technologies are necessary to increase the efficiency of energy systems in future*". This illustrates the political drive in support of UTES. The use of renewable energy technologies with a variable supply further strengthens the need for energy storage.

UTES technologies take advantage of the thermal capacity and large storage volume offered by the underground coupled with its reduced transport velocities and thus lower energy losses to the surrounding environment. Aquifer Thermal Energy Storage (ATES) and Borehole Thermal Energy Storage (BTES) are the two most promising storage options. They are already well established solutions in Canada and Northern Europe lead by The Netherlands followed by Germany and Sweden. The number of systems is still expected to increase significantly in these countries. For example, the Dutch Underground Energy Taskforce estimated a growth rate of approximately 30 %/yr for UTES deployment in The Netherlands, under the proposed policy changes (Bonte et al. 2011). At the same time UTES is penetrating the market in other countries also: for instance a pilot project has been running for several years in the Stockton College lab (New Jersey, USA) and some implementation can be found also in warmer climate countries likes Turkey and Italy.

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As suggested by the name, ATES systems provide cooling or heating using groundwater as the medium of thermal storage and transfer between the aboveground system and an aquifer. During winter, natural or artificial cold is stored while previously stored heat is pumped out. During summer, the stored cold is pumped back and the waste heat from the cooling process or from the external heat source is stored. A heat exchanger transfers the heat or cold from the groundwater to the user. The aquifer is connected by using conventional groundwater wells.

In BTES systems, thermal energy is transferred from the surface to the underground and vice versa by means of thermal conductive flow from a number of closely spaced boreholes. The boreholes are equipped with borehole heat exchangers (BHEs), mostly single U-tubes made of plastic piping. Heat or cold is delivered to or extracted from the underground by a fluid circulating inside the U-tubes in a closed loop, avoiding exchange of mass with the underground. For this reason BTES are often referred to as closed systems. The circulating fluid often contains antifreeze to allow the system at surface to also operate below freezing point. As for ATES, heat pumps can be combined with BHEs and the systems are then called Ground Source Heat Pumps (GSHPs) (IEA ECES Report Annex 20 2011).

232.2 Research Aims

Although UTES are considered environmental friendly solutions they are not completely free of impacts on the underground. They can have hydro(geo)logical, chemical, thermal or microbiological impacts. These possible impacts are obviously strongly interrelated. The risks of UTES to groundwater quality are insufficiently known (e.g. Bonte et al. 2011; Stuurman et al. 2010; Hartog et al. 2013), and policies to address this uncertainty are still lacking. Additionally, UTES require drilling, consume materials for their installation as well using energy to pump water and run a heat pump in the operational phase.

This brings up some important issues that need to be looked into in more detail. When the geological and system requirement conditions allow the installation of both solutions which one is more sustainable? As previously stated UTES have environmental and energy savings advantages but this type of underground exploitation prohibits other uses of the subsurface. Are UTES, given the range of possible uses of the subsurface in an urban environment, the best available technique for exploiting the underground to this end or are there better options for the sustainable use of the subsurface? These questions are of course too wide to be answered within a single study and the answer will be site specific. In order to improve the understanding and knowledge of UTES techniques, this study aimed to perform a Life Cycle Assessment (LCA) on ATES and BTES as a step forward to clarify these more general issues.

232.3 Methodology

Life Cycle Assessment (LCA) is a comprehensive and standardized method used to support environmental policy making and strategic planning, as well as for products development, comparison and improvement in both the public and private sector. By using a range of available impacts methods and indicators environmental impacts, energy demand, and economic and social costs of a product or environmental service can be quantified throughout its life cycle, from the acquisition of raw materials to the end of life scenario.

The LCA of ATES and BTES was performed using the software SimaPro 7 and the Impact Assessment Method Eco-Indicator 99. Moreover a straightforward energy balance calculation was accomplished using the Cumulative Energy Demand (CEnD) method. For more information about the LCA framework and the impact methods used please refer to the ISO standard 14044 and to the SimaPro Database Manual and Impact Library by PRè Consultants (2002–2010), respectively.

This study elaborates on data availability and looks at typical ATES and BTES systems based on data from the literature and collected through personal communication with private companies involved in the installation and operation of such systems. Before evaluating the LCA results it is important to specify the systems and to define their boundaries:

- Capacity: 250 kW. This capacity is chosen in order to allow a comparison between open and closed systems. It is an average power range that represents a small ATES or a large BTES, while maintaining realistic conditions.
- Systems function: heating.
- Functional unit: 25 years. The systems operate 2000 h/year at full capacity.
- Ground composition: sand and clay.
- Water table depth: ~2 m below the surface.
- Climate and underground temperature: average Dutch conditions of 12 °C.
- Disposal of the drilling muds: in open landscapes the drilling muds are usually spread on the surface in proximity to the drilling site. UTES systems are more likely installed in urban zones or locations where the surface use is unsuitable for disposal. Therefore, in the life cycle model disposal of the drilling muds and waste are allocated 50 % to land farming and 50 % to a residual material landfill.
- End of life: the sealing of the pipes or wells with bentonite is taken into account while landfilling of plastic pipes is used as a proxy for underground deposition as

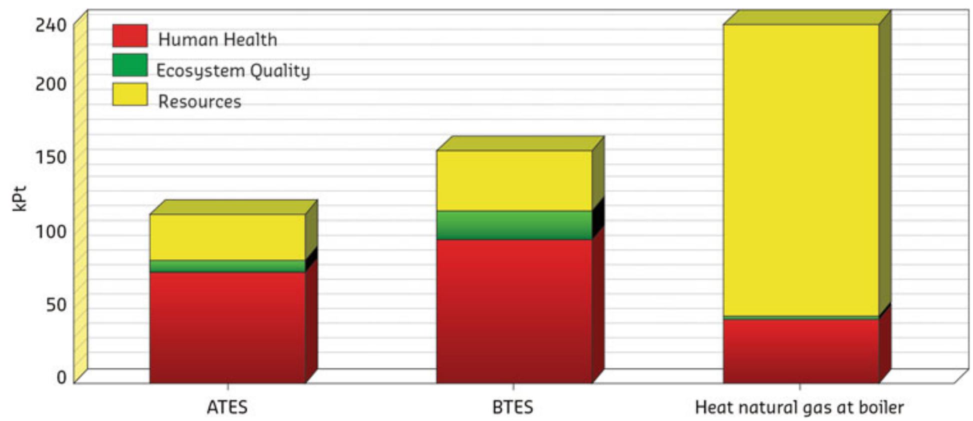


Fig. 232.1 Comparison of ATES, BTES and traditional heating system's single scores, calculated using the Eco-Indicator 99 impact method

this kind of impact is still not included in the LCIA methods.

- Annual regeneration of the ATES wells: ~100 kWh pumping * 25 years = 2500 kWh. Water flushing is the most common practice to regenerate clogged wells. Chemical treatment is rare, because it is undesired and often requires special permission from the competent bodies. Preventive maintenance is done every year by simply extracting water from each well and discharging the water into the sewerage or surface water.

UTES impacts are also compared with the traditional heating system they could replace, like a boiler burning natural gas. The system is chosen directly from the Eco Invent library of SimaPro and the heat provided is of course equal to the heat recoverable with the ATES and BTES considered over the functional unit of 25 years: 4.5×10^7 MJ.

232.4 Results

In this chapter the life cycle impact assessment results and energy balance of ATES and BTES are described, together with an uncertainty analysis.

232.4.1 Eco-Indicator 99

According to the LCA results using Eco-Indicator 99 impact method, UTES might represent better solutions compared to buildings traditional heating systems like natural gas and ATES are more sustainable compared to BTES. Figure 232.1 shows that the single score of ATES (left) is lower than the single score of BTES (middle) and almost half of the traditional heating system's (right) score (a lower score meaning lower impacts). The single score is divided into three Damage categories: Human Health, Ecosystem Quality and Resources. The major damages are associated with the Human Health category. Emission of inorganic substances that can affect the respiratory airways and carcinogenic substances being the main causes.

UTES potential impacts become definitely less important when we consider electricity produced by means of renewable energy sources like photovoltaic panels instead of a European countries mix. The main calculated impacts of UTES are due to the electricity consumption, in particular to the emissions from fossil fuels fired power plants. Indeed, in 2009, 51.3 % of the total gross European electricity production was generated from fossil fuels, more than 25 % of which from coal and lignite (EUROSTAT 2010). Table 232.1 shows to which extent ATES and BTES life cycle processes contributed to the single scores. Electricity is mainly required during the operational phase of the systems for the heat pump use and—to a smaller extent—for the production and re-injection of water.

To maintain objectivity it should be pointed out that the present state of the art of the impact assessment methods does not include the totality of the impacts for these relatively new technologies installed in the underground. For instance, the Ecosystem Quality scores remain very low compared to the other two Damage categories (Fig. 232.1). This is probably due to the fact that EI 99 (as well as all the other impact methods available nowadays) does not take into

Table 232.1 Contribution percentage of the different ATES and BTES life cycle processes to the single score. Cut off: 1 %

Processes	ATES	BTES
Electricity	88.7	80.9
Disposal drilling waste to landfarming (50 % allocation)	3.0	8.6
Polyethylene pipes production	–	4.1
PVC pipes production	4.0	–
Disposal drilling waste to landfill (50 % allocation)	–	2.5
Bentonite	1.8	–
Heat pump production	1.3	–
Disposal polyethylene to landfill (proxy)	–	1.1
Remaining processes	1.2	2.8

account the possible hydrogeological, geochemical, microbiological and thermal impacts derived directly from the production and reinjection of groundwater. At the same time, the Land use Impact category only considers land occupation and transformation at the land surface and not in the underground.

The results presented are valid for the subsurface characteristics and system specifications chosen in this study and might change in case of specific systems with different characteristics and with different geological and climate conditions. Moreover, it is important to underline that the LCA outputs are relative only to a single ATES or BTES system and do not consider the high forecasted number of future installations that might raise additional problems in terms of temporary water stock depletion for ATES and space resource depletion for BTES.

232.4.2 Uncertainty Analysis

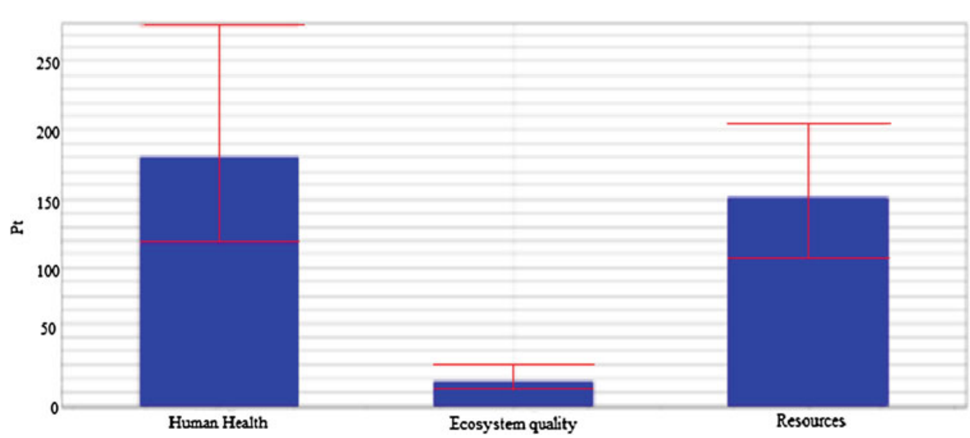
Life Cycle Assessment is a holistic approach that allows a complete vision and evaluation of the issues and impacts related to the systems studied. At the same time, systems and impacts can be complex and exhibit a relatively high degree of uncertainty. The uncertainty related to the inventory data can be quantified using a stochastic method like Monte Carlo analysis. Figure 232.2 shows the results of a Monte Carlo simulation (number of runs: 1000; confidence interval: 95 %) applied to ATES data and visualized for each normalized Damage category. The results of the uncertainty analysis for BTES are very similar as it is for the life cycle processes of the two systems. The coefficient of variation of the single score is 21.4 % for ATES and 25 % for BTES. A methodology to assess the uncertainty associated with the impact assessment models has not been developed, yet.

232.4.3 Cumulative Energy Demand

The Cumulative Energy Demand (CEnD) method aims to investigate the energy use throughout the life cycle of a good or a service. This includes the direct uses as well as the indirect or grey consumption of energy due to the use of, e.g., construction materials or raw materials. CEnD values can be used to compare the results of a detailed LCA study with others where only primary energy demand is reported. Energy consumption is an easily understandable indicator for decision-makers such as consumers, politicians or managers of private companies. But energy/exergy use does not give a complete picture of all environmental impacts in the life cycle of goods and services and the environmental impacts vary across different energy resources. Last but not least, when using the CEnD method it is fundamental to point out that different concepts for determining the primary energy requirement exist and so far there is no standardized approach to this type of assessment method.

When analyzing the total energy requirements with CEnD, UTES performs better in comparison with a natural gas heating system: ATES is again best in terms of performances, with an energy demand 23 % below that of BTES and 40 % lower than natural gas. The life cycle energy savings of UTES are much lower than the primary energy savings suggested in many papers, because these savings calculations consider only the operational phase of the systems. The life cycle energy savings for the considered ATES system is only 30 % against 77 % when only looking at primary energy savings. Similarly, the life cycle energy savings of the considered BTES system amounts to 10 % and 70 % for primary energy savings. Nevertheless the total energy demand for natural gas is even higher than the thermal energy return (−25 %). Moreover, almost the totality of the energy consumed by the traditional heating system has

Fig. 232.2 Uncertainty analysis of the Eco-Indicator 99 damage categories of the open system, calculated with the Monte Carlo method



obviously fossil origins while the electricity consumed by the UTES systems can also derive from renewable sources.

232.5 Conclusions and Recommendations

UTES technologies represent a possible solution to reduce overall energy depletion as they allow buffering the seasonal difference between energy supply and energy demand. The effect is exacerbated when combined with renewable energy production. This LCA study sets a basic framework to investigate UTES sustainability providing quantitative results. It contributes to the increasing number of LCA's applied to environmental services obtained from the subsurface. Based on the LCA results using the Eco-Indicator 99 impact method, UTES represents a better solution compared to a traditional heating system for buildings like natural gas and the open system is associated to lower impacts compared to the closed system. A similar output is obtained using the Cumulative Energy Demand method. Even with the life cycle energy savings being, much lower than the primary energy savings, as expected, ATES life cycle uses 40 % less energy than a boiler burning natural gas and providing the same amount of heat, while the correspondent figure for BTES is 23 % energy reduction. On the other hand the LCA methodology—especially as far as the subsurface is concerned—is still incomplete. This makes quantification of the real risks connected to UTES more problematic. It is still unclear whether—from a future perspective—UTES should represent only a transitional expedient or a final solution. For this reason further research in terms of databases improvement and impact method models development is strongly recommended. The list of included impacts should be extended and a methodology to quantify the uncertainty associated with the models used in the impact methods should be developed.

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