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Planning and Constructing Cost-Effective Very Large-Scale Hot Water TES for District Heating Systems

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Abstract

In an international context (Germany, Denmark, Sweden, Canada and China), the integration of long-term thermal energy storage (TES) into block heating systems already exists. Yet, the so-called pit TES cannot be easily applied to central European block and district heating systems because of the varying heat demand, temperature level, TES size, TES geometry, ground conditions (e.g. presence of groundwater), etc. Thus, within the framework of the Austrian Flagship project Giga_TES (FFG), very large-scale underground tank or pit TES are developed and optimized by means of simulations. The aim is to provide solutions that enable a significant reduction of fossil fuels needed in district heating systems. This can be achieved through an optimized design of a multifunctional TES allowing short-term as well as long-term heat storage with appropriate dimensioning and optimal planning of solar thermal, waste heat use and heat pumps for a specific location and system. The envisioned size of new giga-scale storage technologies and the construction in the subsurface require new construction methods. Experiences show that improvements are needed on material performance and durability and on materials and component development. Cost effectiveness and system integration call for higher storage density and thus, higher temperatures, imposing even higher demands on the materials used. This and the requirements of vapor tightness, serviceability and durability of innovative solutions for cover, wall and bottom with respect to liners and insulation call for novel materials and construction methods. Hence, numerical models are developed to optimize the thermal, structural, system integration and economic performance of materials, components and system.
This contribution highlights the challenges of constructing cost efficient giga-scale TES. Different construction methods for tank and pit TES are compared with respect to their investment costs. The thermal performance of the different TES is compared by means of numerical simulations for a set of boundary conditions.

Keywords: Seasonal thermal energy storage, Buried tank, Buried pit, Planning, TES performance, Cost.

1. Introduction

It is held that one of the best engineering solutions to meet the heating demand in the buildings is by means of district heating (DH) systems. These systems have proven their effectiveness in fulfilling the end-users’ demands (e.g. domestic hot water, space heating). However, DH systems are broadly conventional based systems, which means they employ fossils (e.g. gas) as main energy source [1]. Therefore, there have been attempts to integrate renewables in the DH scheme in order to boost its effectiveness and its role in mitigation of emissions. Solar energy seems to be the most promising source to fulfill the heat demand. Therefore, research has been ongoing to address the applicability and potential of the so-called solar district heating (SDH) systems [2].

There will be always a mismatch between the heating demand and waste or solar heat availability because the high heat demand is remarked in winter season, whilst the solar heat is available during summer. Therefore, there is a definite need for a complimentary element in SDH to capture the solar heat in summer and release it when it is needed during winter [3]. Accordingly, thermal energy storage (TES) is an effective component to bridge the gap between supply and demand of energy and overcoming the intermittency in renewables. Down to these benefits, TES is strongly endorsed in solar thermal applications.

TES systems can be found as short-term systems or long-term storage systems. The first type has a storage period of few days and it is therefore commonly known as diurnal storage. While the storage period can last up to several months in the long-term type forming the so-called seasonal thermal energy storage (STES). This concept permits to store, for example not limited; the solar thermal energy collected in summer. Then, TES releases the stored thermal energy for heat demand in winter. Thus, this concept contributes remarkably to the efficient utilization of renewables in SDH systems and plays a great role in the decarbonization of heating sector.

Given the fact that DH systems employ water as a heat transfer fluid (energy carrier), it is seen beneficial to utilize water as storage medium in STES and this accordingly demonstrates that STES operate with sensible method. Moreover, it is vital to highlight that DH systems can operate with either high temperature or low temperature characteristics. Therefore, this paper explores the role of tanks and pits in high-temperature (i.e. 90°C/60°C) and low-temperature (80°C/30°C) DH systems. To drive a thorough comparison, different key performance indicators (KPIs) are utilized for executing a techno-economic analysis.

2. Frontiers and Challenges of Seasonal Thermal Energy Storage

Seasonal TES systems are increasingly installed in large-scale solar heating applications due to their capability to eliminate the seasonal discrepancy between solar heat abundance in summer and the space heating demand in winter. Yet, the planning and construction of large-scale STES are often seen challenging technically and economically. This is strongly attributed to the fact that such systems require great volumes to fulfill the seasonal tasks and, therefore, large space availability is needed. Hence, these systems are often located near the ground surface or buried (fully or partially). Consequently, these systems are often known as underground thermal energy storage (UTES). Underground TES can be classified following their construction into: (1) aquifer TES, (2) borehole TES, (3) tank TES, and (4) pit TES [4].

Due to their applicability in both low- and high-temperature DH systems, this work investigates only the last two options (tank and pit TES systems). Though the TES types list is narrowed down to two options, this does not condense the challenges in their construction because later different questions in context of the construction type (e.g. partially or full buried) and geometry (e.g. tank, truncated cone or pyramid stump) arise during the planning phase. Figure 1 demonstrates the interrelated process with the different categories.

Most recently, Dahash et al. [3] emphasized that both of the construction type and geometry have a significant impact on the efficiency and the economic feasibility of the chosen storage. Despite the technical conventionality of cylindrical tanks, they are often costly in context of construction and installation. Hence, one major downside is the high investment cost associated with their construction. Alternatively, pyramid stump or conical pits arise as a good practical engineering option that reduces remarkably the investment cost. However, the pit performance is often lower than that of the tank. Therefore, it is necessary to address the applicability of each option for a given a volume and a certain set of operation characteristics.

Thus, in framework of an international project entitled "*Giga-Scale Thermal Energy Storage for Renewable Districts*", a crucial milestone is to set the planning guidelines for each construction type and geometry in different DH schemes. Accordingly, this work contributes to these guidelines by investigating the impact of DH system characteristics on seasonal TES, the impact of construction type and geometry on performance and the impact of thermal losses on ground.

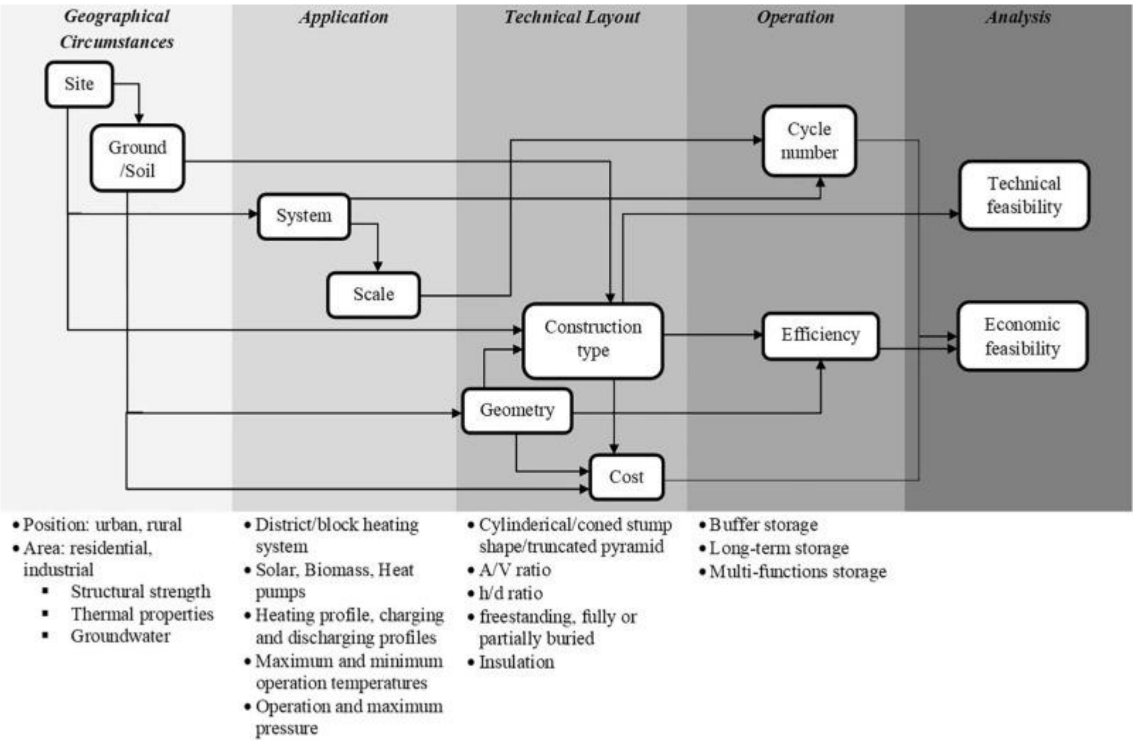


Figure 1: Schematic representation of the most influencing parameters and their dependencies on the construction of large-scale underground TES [3]

3. Methodology

3.1 Development of the Numerical Model

A numerical multi-physics model was developed in COMSOL Multiphysics to inspect the thermal behavior of a seasonal thermal energy storage with different geometry options (pit and tank) in a DH system as shown in Figure 2 [5]. To avoid costly system simulations in terms of computation, standard high and low temperature DH profiles (namely flowrates and temperatures) were introduced to represent the characteristics of the system. Figure 3 shows the periodic operating conditions for a TES with a volume of 100,000 m^3 in low- and high-temperature DH system. Moreover, Table 1 shows the dimensions for both storage types (tank and pit).

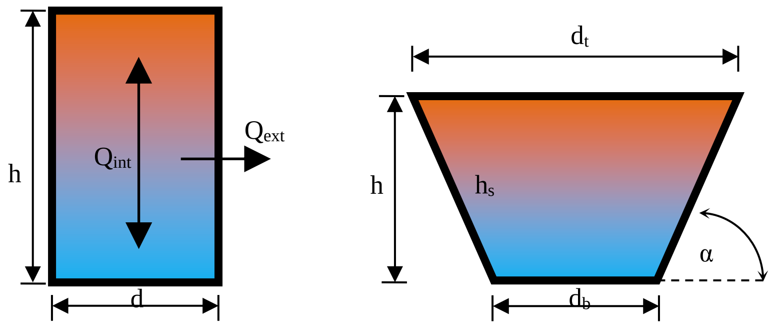
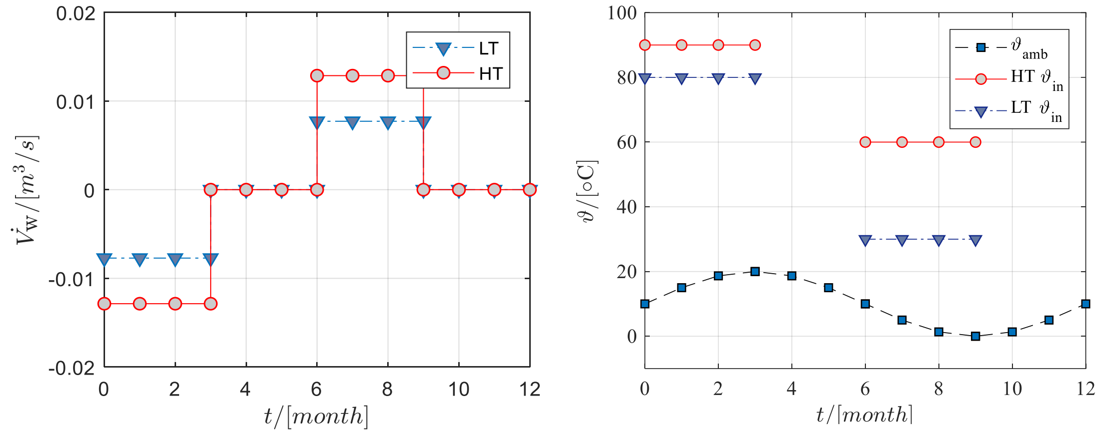


Figure 2: Geometry of a buried seasonal thermal energy storage with internal and external losses: (a) tank, (b) pit.



(a) Water volumetric flowrate as a periodic function of the time for a TES with a volume of 100,000 m^3.

(b) Flow temperature as a periodic function of the time and ambient temperature as a sinus function with an average of 10°C.

Figure 3: Simplified operational conditions for a low- and high-temperature DH systems

Table 1: Dimensions of the storage types

Parameter	Tank	Pit
Height, H	50 m	50 m
Base diameter, d_b	50.5 m	20 m
Top surface diameter, d_a	50.5 m	75.7 m
Slope angle, α	90°	60.9°
Volume, V	100 000 m^3	100 000 m^3

Table 2: Properties of the materials and heat transfer coefficients (HTC) of the different components in TES

Parameter	Value
Water thermal conductivity, λ_w	0.6 W/(m.K)
Water density, ρ	1000 kg/m^3
Water specific heat capacity, c_p	4200 J/(kg.K)
Overall HTC of the cover, U_{cover}	0.1 W/(m^2.K)
Overall HTC of the wall, U_{wall}	0.3 W/(m^2.K)
Overall HTC of the bottom, U_{bottom}	0.3 W/(m^2.K)
Ground thermal conductivity, λ_g	1.5 W/(m.K)
Ground specific heat capacity, $c_{p,g}$	880 J/(kg.K)
Ground density, ρ_g	1000 kg/m^3

If more information is needed about the development of the numerical model, it is fully described with other large-scale TES models in [6].

In fact, constructions of cylindrical tanks with a defined slope of 90° can be realized using a technology referred to as special geotechnical work, whereby the most promising concept is installing a diaphragm wall. Alternatively, bored pile walls can be utilized. For the volume of a 100000 m^3 investigated in this work, the tank can be built as a cylinder. For larger tank volumes where the increase occurs in the tank diameter, the anchors are vital components to provide supplementary reinforcement to the structure. Moreover, it is more likely to construct the tank as cuboid in this case to avoid some structural risks (e.g. breakout cracks).

On the other hand, different construction technologies (e.g. anchors, soil nailing, reinforced soil etc.) could be adopted to accomplish pits with a slope of 60°. It is also possible to construct a pit with a natural slope up to 30°, however; this depends on the soil quality. The pits are built in a geometry of either a truncated cone with circular cross-section, or more likely a pyramid stump with a rectangular cross-section. For both storage types (tank and pit), it is more economic to utilize the excavated soil for building an embankment.

For a 100000 m^3 storage volume, the natural slope pit can be realized with a depth down to 32 m. To provide more comparability, the pit is assumed to be built with a depth of 50 meters as the depth of tank and, therefore, the pit slope is approximately 60°.

3.2 Performance Indictors and Costs

In this work, the efficiency of a TES can be determined by the ratio of annual thermal losses to the maximum theoretical storage capacity and expressed as below:

$$\eta_{\mathrm{sto}} = 1 - \frac{Q_{\mathrm{loss}}}{Q_{\mathrm{sto}}} \tag{1}$$

It is important to pay a considerable attention that there exist some other definitions for storage efficiency and they are well discussed in the literature. In this work, however, the suitability of the chosen definition is observed since it correlates the overall thermal losses to the maximum capacity, so it indicates directly the effective volume of the storage. Therefore, this efficiency definition is less sensitive to TES operation.

For the economic analysis of TES construction, the total investment cost is calculated considering the different contributions in the investment cost. Such contributions are the excavation, diaphragm wall, cut-off wall, insulation, liners, cover, plant construction and site facilities.

Table 3: Different specific costs for the construction of seasonal TES

Contribution	(Specific) Costs	Remark
Excavation	20 €/m³	Partly wet excavation
Diaphragm wall	550 €/m²	50 m deep
Cut-off wall	50 €/m²	In case of ground water in 5 m distance
Insulation	100 €/m³ 200 €/m³	Bottom (pressure resistant) Wall (including installation)
Liner	150 €/m² 50 €/m²	VA, Stainless steel (HT) Polymer liner (LT)
Cover	200 €/m² 800 €/m²	Floating cover (50 cm ins.) Trafficable floating cover
Plant construction	40000 €	Independent TES construction
Site facilities	50000 €	Fixed

Under the given TES depth (i.e. 50 meters), diaphragm walls are perfectly suited for the construction. Whereas the cut-off wall is installed, if groundwater exists. When it comes to the liner cost, it is important to differentiate between liners applicable for LT and HT systems. Given the high temperature, the liner in is made of stainless steel (VA). Whilst polymer lines are applicable for LT systems. Moreover, the insulation applied on the storage bottom should be able to provide pressure resistance.

For the economic analysis it is according to the theory of investment possible to represent an investment with annual fixed payments. Assuming a service life of n = 50 yrs. (or n = 20 yrs. for the polymer liner) and a discount rate of i = 3 % the annuity factor ANF

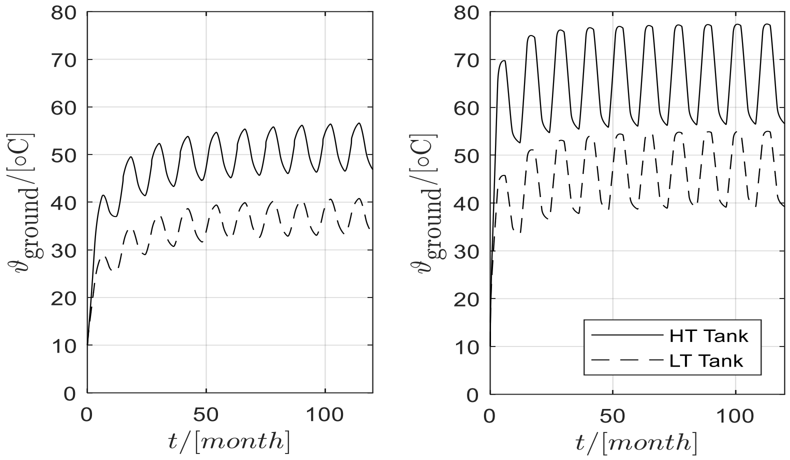
$$ANF_{n,i} = \frac{(1+i)^n \cdot i}{(1+i)^n - 1} \tag{2}$$

is 3.9 % or 6.7 %, respectively. With the annuity factor investments with different lifetimes can be compared or the annual payment can be compared with the annual savings e.g. due to enhanced efficiency and thus reduced thermal losses.

4. Results and Discussion

Simulations were presumed to start on May 1st of each simulation year during which the charging phase starts and, then, over a course of three months the storage is injected with solar energy collected by means of hot water. This phase is followed by a 3 months storage phase. Next, the discharging phase takes place followed by a 3 months of idle phase. The simulation timespan was set up to run over a 10 years period permitting the STES system to reach its operating capacity and to allow the ground to pass the preheating. A single-day simulation time steps were utilized in the numerical model. However, shorter timespan did not provide significant changes in results.

For both high and low-temperature DH systems, average ground temperature over the simulation period are shown in Figure 4. After 50 months, the average ground temperature peaks at around 55°C for the high-temperature system in case of insulation. This leads to less thermal losses after the preheating phase and, therefore, improved performance can be anticipated. The low-temperature system peaks at a temperature of about 40°C. The ground temperature was examined at the interface line between the storage and ground.



(a) With insulation (b) With no insulation

Figure 4: Ground temperature over the course of 10 years for HT and LT systems with a ground thermal conductivity λ_g = 1.5 W/(m.K)

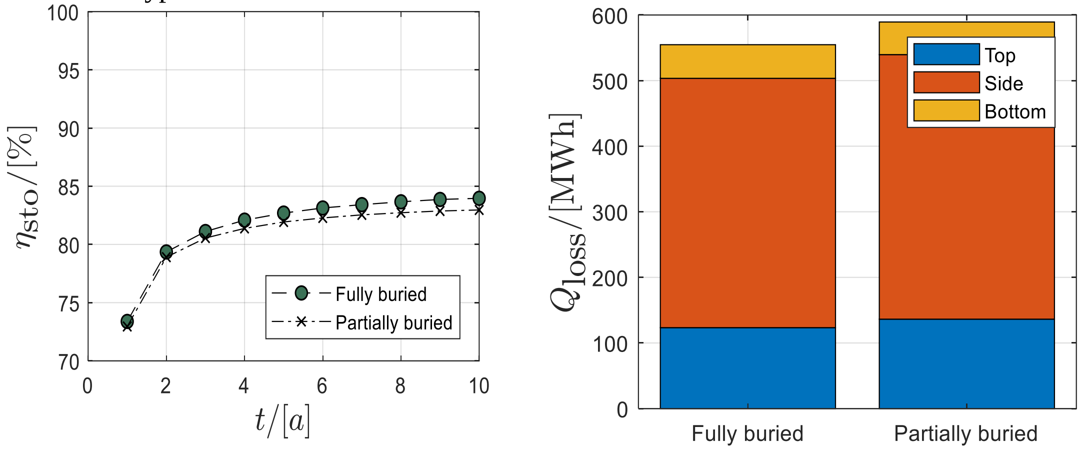
The minimum ground temperature is observed during the discharging and idle phases of storage and it is due the return temperature from the load, and it is approximately 45°C and 32°C for the high and low temperature systems, respectively.

Yet, the ground temperature can be highly influenced by many factors, e.g. ground thermal conductivity, storage envelope thermal transmittance, groundwater flow and system temperature. In Figure 4 (b), a special case is shown where no insulation encloses the storage. It is clearly demonstrated that under such circumstances, the ground temperature rises for higher values in low-temperature systems compared to the values from a high-temperature system in case of insulation. Accordingly, this draws attention to a critical topic concerning the preservation of ground and maintaining an acceptable temperature. In some countries, it is vital to maintain the ground temperature below a given range (e.g. 25°C to 30°C). Inevitably, it is then essential to use more insulation in order to maintain an acceptable temperature of ground. This additional volume of insulation is not technically required for storage; instead, it is required to follow the hydro-geological standards for ground temperature.

4.1 Impact of TES Construction Type and TES Geometry

When planning and designing a large-scale seasonal TES, a special attention should be paid to the space availability and the social acceptance. Thus, these systems are mostly buried either fully or partially. Given the fact that air temperature varies with a range different to that of the ground, there could be some differences in performance between the partially and fully buried TES.

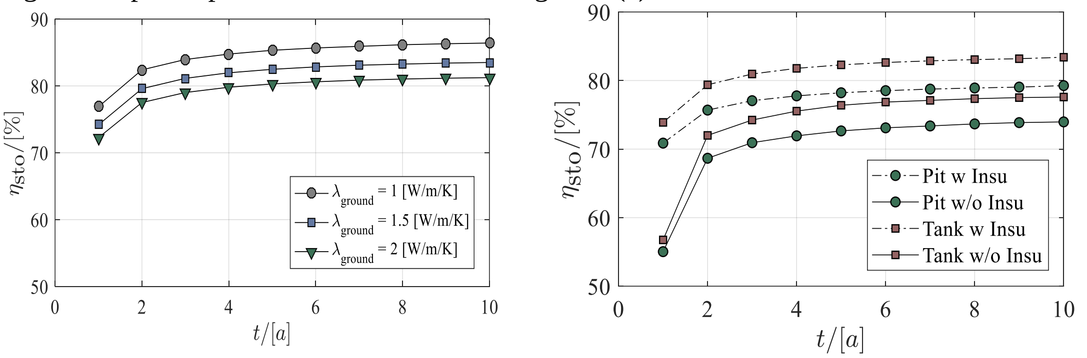
Figure 5 reveals the storage performance for the two aforementioned options. The partially buried storage is aboveground with a height of 15 meters, whereas the rest is buried. It is undoubtedly shown that, under the given boundary conditions (i.e. fully insulated), there is no major difference in the performance whether the storage is fully buried or partially. This is because the partially buried TES losses more energy to the ambient air than the fully buried one and, consequently, this yields a drop in water temperature inside the partially buried TES. On the other hand, the fully buried TES losses more energy to the ground due to more lateral area buried in ground. Figure 5 (b) reveals the breakdown of the different contributions of thermal losses from both construction types.



(a) Storage efficiency (b) Storage thermal losses

Figure 5: Storage efficiency and thermal losses for a given storage volume of 100,000 m^3 with a ground thermal conductivity $\boldsymbol{\lambda_g}$ = 1.5 W/(m.K) and with two construction types; partially and fully buried.

Having seen no major difference in performance, the work will consider only fully buried TES further. Additionally, the work also investigated the influence of ground thermal conductivity on storage efficiency. It can be observed that with lower values of ground thermal conductivity, the storage has superior performance as shown in Figure 6 (a).



(a) Storage efficiency during the 10 years of operation for different ground thermal conductivity.

(b) Storage efficiency during the 10 years of operation with a ground thermal conductivity λ_g = 1.5 W/(m.K).

Figure 6: Storage efficiency for different cases

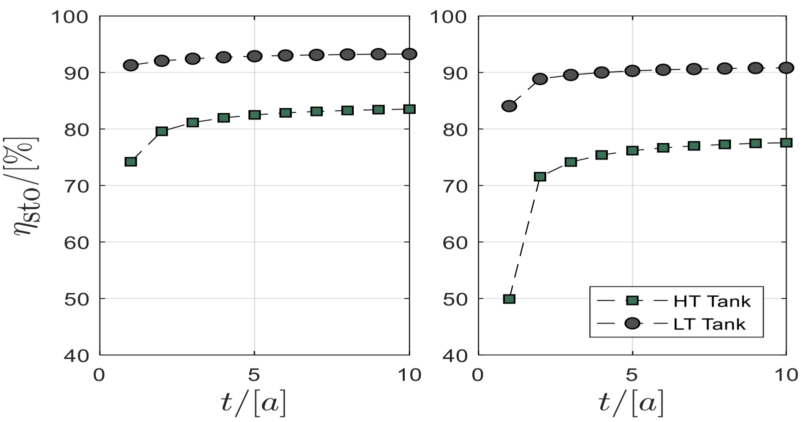
Intrinsically, there exist some differences between the different geometries of buried TES from a thermodynamic point of view. Therefore, the following of this section underlines a comparison between a conical pit and a tank in a high temperature DH system from a thermodynamic point of view. The comparison includes two cases: (a) with no insulation, and (b) with no insulation.

Figure 6 (b) compares two different geometries, a conical pit and a tank. The comparison confirms that the tank outperforms the pit no matter what insulation thickness encloses the storage. It is also revealed that the efficiency of a tank with no insulation approaches closely the efficiency of a pit with insulation. Therefore, it is important to pinpoint the investment cost, which a pit with insulation brings compared to that of a tank with no insulation. Yet, it is also presented that low performance values of around 55 % were recorded for both tank and pit after a year of operation with no insulation. Then, the performance started to develop positively and reached up to 70 %.

One major drawback of no insulation case is the ground temperature that could violate some hydro- geological standards and, therefore, the insulation could be needed only and solely to preserve the quality of the ground (see Figure 4).

4.2 Performance Evaluation

An important consideration in a large-scale seasonal TES system is the ratio of storage volume to surface area (A/V), which directly has an impact to the external thermal losses from the storage. For a given storage volume of 100000 m^3, Figure 7 depicts that seasonal tanks in low-temperature DH systems has better performance than those installed with same capacity and similar boundary conditions in high-temperature DH systems. This can be attributed to the DH characteristics as it is believed that lowering supply and return temperatures might result in less thermal losses and, accordingly, better performance.



(a) With insulation (b) Without insulation

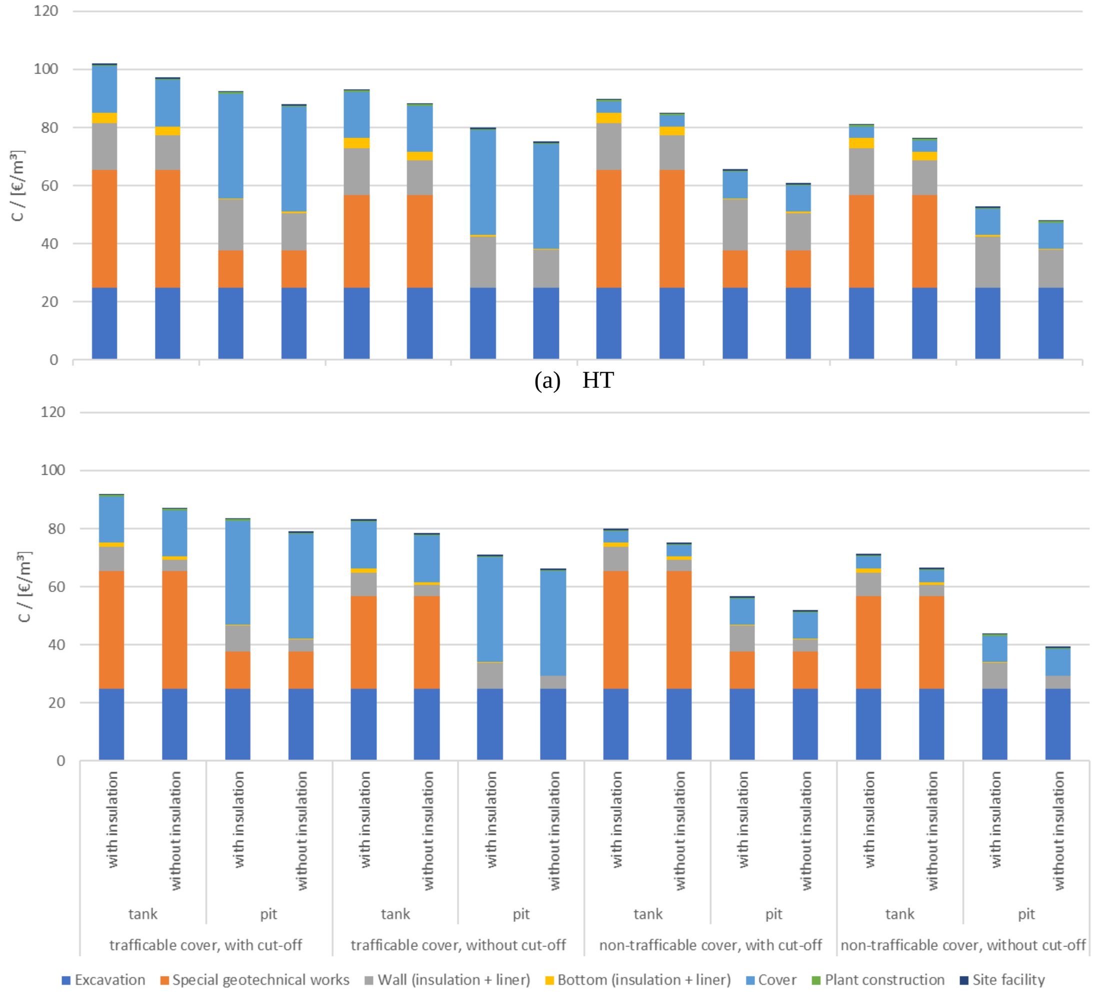
Figure 7: Evolution of tank performance over a time span of 10 years of operation in low- and high-temperature DH systems for two cases: (a) with insulation, and (b) without insulation. Each with a ground thermal conductivity λ_g = 1.5 W/(m.K)

Another player in this scheme is the ground temperature and thermal conductivity. For HT DH systems, the average ground temperature can reach up to 55°C, whereas the return temperature is set to 60°C. Accordingly, there will be always a heat transfer from the storage to the ground driven by this temperature difference. On the other hand, the high efficiencies observed for LT DH are a direct result to the reverse heat transfer. In other words, the average ground temperature is 35°C, whilst the return temperature is given at 30°C and, consequently, there will a reverse heat transfer from the ground to the storage. As a result, the storage water is preheated by this mechanism and, therefore, leading to lower net annual net thermal losses.

Another important case is the storage performance when no insulation encloses the storage. Figure 7 (b) shows the evolution of storage performance over the investigation period and it reveals that the tank performance starts with poor performance of around 50 % in case of HT DH systems. Later, the performance starts to develop remarkably scoring 75 % in the 5th year. This significant increase in storage performance (case no insulation) is strongly accredited to the ground preheating. During the first 5 years, the storage is still in its start-up operation and, consequently, higher thermal losses.

4.3 Economic Analysis

Error! Reference source not found. and Figure 8 demonstrate that total specific costs for STES range from 34 €/m³ (for a pit without insulation non-trafficable cover, without cut-off wall and with polymer liner (LT)) up to 102 €/m³ (for a tank with insulation, trafficable cover, cut-off wall and stainless steel liner (HT)). This difference is highly influenced by the factors shown earlier in this study. Therefore, it is important to quantify the influence of each factor for both aspects (economic and technical) and evaluate whether it is beneficial to tackle this influence or neglect it in case of minor influences.



(b) LT

Figure 8: Breakdown of the total specific cost for TES types with 100 000 m³.

Despite the better thermal performance of tanks, **Error! Reference source not found.** and Figure 8 emphasize that construction of tank is always more expensive than the pit by around 25 €/m³ to 40 €/m³ under the same boundary conditions. It is also observed that cut-off wall is less expensive than insulation (by approx. 1.5 €/m² to 2.5 €/m³), but it is but less effective in terms of losses and ground water overheating protection. 5 €/m³ is approximately the difference between insulated and non-insulated (wall and bottom) pit or tank. Moreover, installing a cut-off wall in addition to the insulation results in an increase 2 €/m³ for the tank, and 3 €/m³ for the pit. Difference between LT and HT is 10 €/m³ for the tank and 9 €/m³ for the pit. Trafficable cover has a most significant influence on the costs for the pit and also for the tank (required space for TES and TES construction is not considered here). Trafficability adds 12 €/m³ for the tank and 40 €/m³ for the pit. For a shallow pit (slope 30 °), trafficable cover is adding 80 €/m³ and thus not an option).

5. Conclusions

Large-scale seasonal thermal energy storage systems gain an increasing significance in the global energy scheme. Due to the long storage period of heat, thermal losses can become eventually substantial if the storage is not suitably insulated. Thermal insulation plays a role in both, the cost optimization of a storage system as well as the necessity of avoiding overheating of the ground in particular in presence of ground water. In this article, different operation aspects and different TES geometries are compared in terms of performance and construction cost.

There are many factors to take into consideration when assessing large-scale seasonal TES systems. These factors can be a multiple of it when the situation comes to evaluate the entire DH system. There is a great difference in the storage efficiency for the two systems (LT and HT) and this difference expands when no insulation is utilized over the storage.

It can be demonstrated that due to the lower temperature difference between the storage and the surrounding ground, the efficiency of a LT system is far superior to that of the HT system in case of tanks. Economically, the difference between LT and HT is 10 €/m³ for the tank and 9 €/m³ for the pit, respectively. This implies the profitability and applicability of LT DH systems.

The storage efficiency differs from a geometry to another. Having shown the TES performance for a tank and a conical pit, it can be observed that the tank outperforms the pit under the same boundary conditions, but the investment cost can be a major barrier. A tank with no insulation (or even poor insulation) can approximate the efficiency of an insulated pit as shown. However, the insulation is sometimes inescapable due to some regulations or standards that preserve the quality of groundwater by maintaining ground temperature below a specific value or range. In this context, the cost of insulation with the required thickness are important to address. From the economic point of view with actual heat prices such a large-scale TES is not yet competitive, but it is one of the rare technological options towards a more sustainable energy system.

Acknowledgements

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