

# The Challenge of Planning and Constructing Large-Scale Hot Water TES for District Heating System: A Techno-Economic Analysis

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**Abstract**--In an international context (e.g. Germany, Denmark), 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 district heating (DH) systems because of the varying heat demand, temperature level, TES size and geometry a ground conditions (e.g. presence of groundwater), etc. Thus, within the framework of the Austrian Flagship project Giga\_TES (FFG), very large-scale underground TES are developed and optimized by means of simulations. The aim is to provide solutions that enable a significant reduction of fossil fuels that traditionally are needed in DH 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 together with the requirements of vapour 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:** *Buried TES, seasonal TES, techno-economic, numerical modelling, shallow pit, tank.*

## 1. INTRODUCTION

Growing concern about environmental and social issues related to climate change is prompting institutions to present a concrete plan to reduce CO<sub>2</sub> emissions. In 2020 the European Union has raised to 55 % the emission reduction target for greenhouse gases by 2030 [1]. In order to reach this goal, the energy system needs to face an important transition to reduce the share of energy from fossil-based sources and replace it with an increasing share of renewables

(RE). The building sector represents an important element in this transition, since it consumes 35 % of global final energy use; more specifically in the colder Nordic European countries space heating accounts for 65 % of total final energy demand in buildings [2]. In particular, District Heating (DH) covers an important share of the energy demand in northern Europe, and it mostly relies on fossil-based plants [3].

The decarbonisation of DH is therefore an important step in the green transition of the building

sector; however the integration of RE presents a critical limit connected to their intermittent availability. For example, solar thermal (ST), which is currently a mature technology widely employed in both residential and district applications, presents daily and seasonal oscillations which limit its ability to cover the winter peak demand in cold climates. In this regard, the integration of a seasonal thermal energy storage (TES) represents a key step for increasing the RE share in the energy system, since it allows to bridge the gap between the energy production (in summer) and the peak heating demand (in winter).

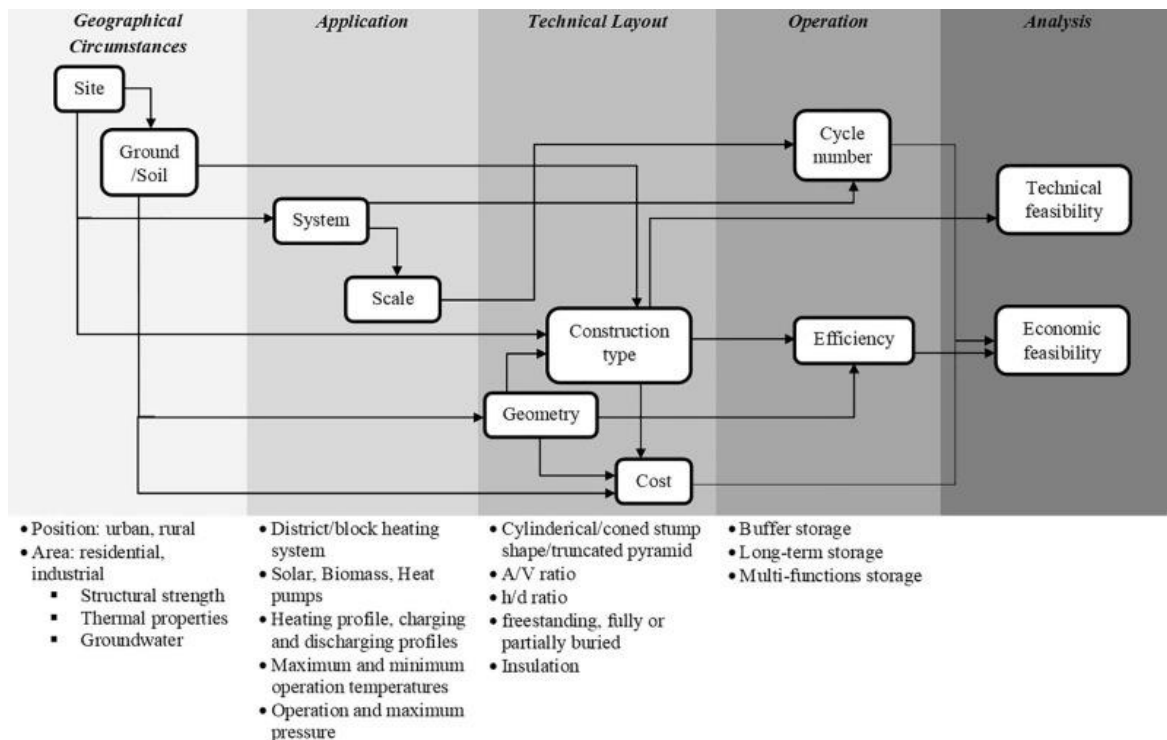
Thus, TES is a common back-up equipment for DH systems in Denmark, which is currently the leader in the application of this technology [4]. The Dronninglund DH in Denmark is a good example for a solar DH system equipped with a seasonal thermal energy storage (STES) to penetrate the share of RE. Here, a 60 000 m<sup>3</sup> pit TES was implemented in 2014 in order to increase the solar fraction by around 20 % [5].

Moreover, it is important to highlight that the application of large-scale TES is not only limited to coupling with ST, but can be efficiently employed with other heat sources, such as industrial waste heat and in combined heat and power (CHP) plants. By virtue of this configuration, TES is capable to decouple partially the power grid and the DH networks

and, thereby, it maximizes the profits [6]. However, though this type of TES belongs to the large-scale one (up to several thousand cubic meters), it is often a weekly storage system and, therefore, it is not further discussed in this work from an operational point of view.

Accordingly, it is held that a large-scale and long-term TES enables a more flexible and smoother integration of RE in DH systems and, as a result, has benefits in terms of lower fossil fuels consumption and, subsequently, higher primary energy savings and lower emissions [7]. Yet, the high investment cost linked to STES is frequently a key downside. Together with the space availability, complex planning layout and the presence of groundwater tables, these are the set of major challenges in STES domain to be tackled among others [8].

To expand the benefits of a seasonal TES, the optimal designing and sizing of STES and its relevant components (e.g. charging/discharging devices) should be adequately planned. Substantially, planning and construction of large-scale seasonal TES is a complex process. Dahash et al. [7] illustrated the high number of inputs that should be taken into account in the overall planning and have a significant impact on efficiency and economic feasibility (see **Figure 1**). In the following section, the challenges in the planning phase are thoroughly discussed.



**Figure 1** Schematic representation of the most influencing parameters on the construction of large-scale TES [7].

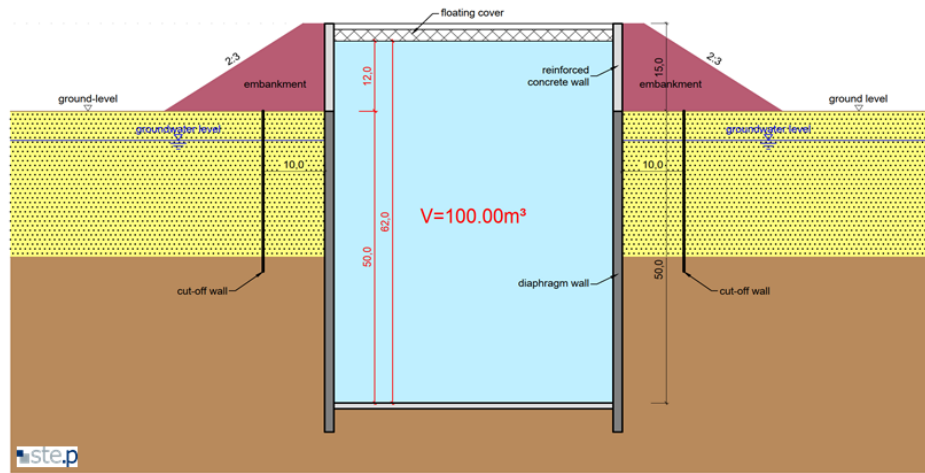
## 2. CHALLENGES IN PLANNING AND CONSTRUCTION

To select properly the design, geometry and construction type for a large-scale seasonal TES, a great number of inputs (hydro- geological factors, system characteristics, thermal losses, investment cost, etc.) have to be visited repeatedly until a decision is made in which a compromise between the technical performance and the economic investment is found. **Figure 1** exemplifies the interrelated process with the different categories.

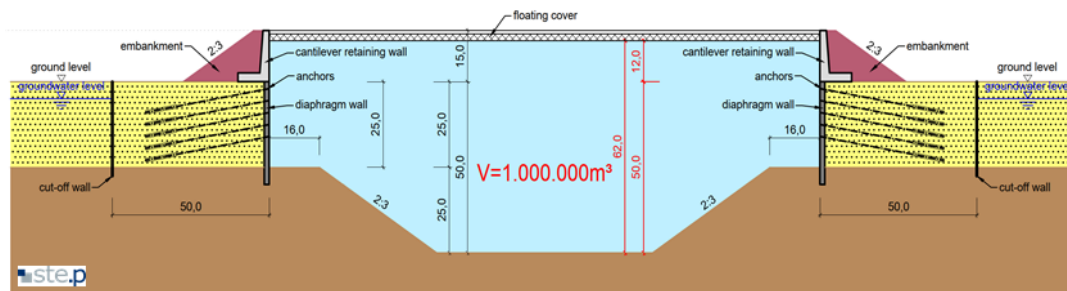
Despite the technical conventionality of cylindrical tanks for volumes of some 10 000 m<sup>3</sup>, one major

drawback of them is the high investment cost. As an alternative, 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. All these technical and economic barriers imply a need to find an optimal STES that satisfies the goals of producing a highly efficient and feasible storage type.

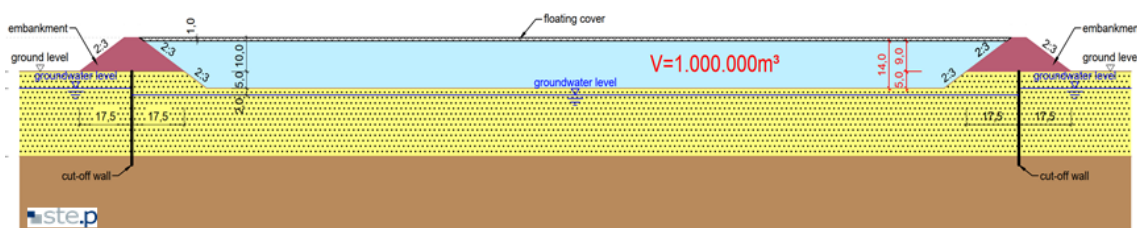
Thus, in framework of the international project “Giga-Scale Thermal Energy Storage for Renewable Districts” (*giga\_TES*) [9], an ultimate milestone is to set the planning guidelines for each construction type shown in **Figure 2**.



(a) Underground tank with embankment of  $H = 15$  m



(b) Hybrid TES - Tank in combination with pit



(c) Shallow pit (“Danish TES”)

**Figure 2** Different geometries and construction types considered in framework of the Giga\_TES project.

The goal of the project was to set guidelines that could help engineers and researchers to identify the most effective construction type for the given task and to withstand the relative challenges [10].

In this study, the authors will present a comparative study between different construction types and geometries thus extending the knowledge introduced in [8] with the most recent results and developments. For instance, the paper will investigate the influence of construction type and of the TES geometry (tank or shallow pit) on the storage performance and cost and will present a range of costs based on the available technological solutions and on the possible developments of the materials and installation procedures. Moreover, for the sake of a comprehensive comparison, the paper includes a comparison between two types of storage (tank and shallow pit), where in one case insulation is applied only on the cover (referred to as “without insulation”) and another case with fully insulated TES (“with insulation”).

Storage systems of such large-scale are characterized by significant thermal losses because of the large interaction area between the tank lateral (and possibly the bottom) area and the ground; thus, it is important to enclose underground TES systems with thick insulation layers. These insulation materials can be introduced in the envelope either inside or outside in addition to the main sidewall construction material (e.g. concrete, steel, reinforced concrete, etc.); however, the material characteristics (e.g. hygroscopic behaviour, ageing) should be taken into account in the material selection during the design phase. Thereby different schemes can be observed for the composite sidewalls (see **Figure 3**).

Accordingly, in this work the impact of the envelope configuration on the reduction of the thermal losses and on the investment costs will be analysed.

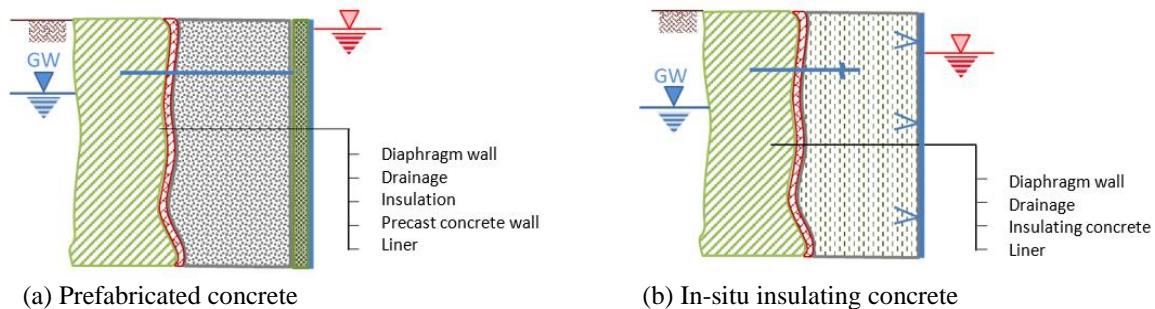
The dimensions for both storage construction types (tank and shallow pit) for different volumes between 100 000 m<sup>3</sup> and 2 000 000 m<sup>3</sup> are shown in **Table 1** and **Table 2**. Different geometries and design solutions concerning the presence of an embankment dam are considered. In particular, for the tank TES, the possibility to include a dam of 15 m is considered alongside the solution without dam for the tank TES with 50 m height (**Table 1(a)**). A tank TES with 65 m total depth and a 15 m dam (**Table 1(b)**) is also considered in the cost analysis to evaluate the impact on the earthworks. While for the shallow pit TES four solutions are analysed: with 5 m dam and without dam with low aspect ratio ( $h/d$ ) (**Table 2(a)**), and then with high  $h/d$  and optimised dam height (to balance the excavated volume and the volume of material required to build the dam) and with high  $h/d$  and no dam (**Table 2(b)**).

### 3. NUMERICAL METHODS

A numerical multi-physics model was developed in COMSOL Multiphysics® to study the behaviour of a seasonal TES with different geometry options (tank and shallow pit) in a DH system [8].

**Figure 4** shows a 2-D sketch for an underground conical pit with a symmetry axis ( $r=0$ ). To capture the advantages of the axisymmetric feature that can reduce the number of degree of freedom producing less computation time, it is assumed that the shallow pit shown in **Figure 2(c)** has a circular cross section while maintaining the total volume, the top and bottom surface area.

In order to avoid costly simulations in terms of computation, simplified DH profiles of a high temperature TES (HT TES) (namely flowrates and temperatures) were introduced to approximate the characteristics of the system [8].



**Figure 3** Example of configurations for TES wall construction investigated in framework of Giga\_TES project.

**Table 1** Tank dimensions for the different tank TES volumes considered in this work. (a) 50 m deep tank with 15 m dam and without dam. (b) 65 m deep tank with 15 m dam.

(a)	Case 1	Case 2	Case 3	Case 4	Case 5
Dam height, $h_{dam}$ [m]	[0, 15]	[0, 15]	[0, 15]	[0, 15]	[0, 15]
Height, $h$ [m]	50	50	50	50	50
Diameter, $d$ [m]	50.46	71.36	112.83	159.57	225.67
Area, $A$ [m <sup>2</sup> ]	11927	19210	37725	65066	115449
Volume, $V$ [m <sup>3</sup> ]	100 000	200 000	500 000	1 000 000	2 000 000
$h/d$ [-]	0.991	0.701	0.443	0.313	0.222
$A/V$ [1/m]	0.119	0.096	0.075	0.065	0.058
Slope, $\alpha$ [°]	90	90	90	90	90

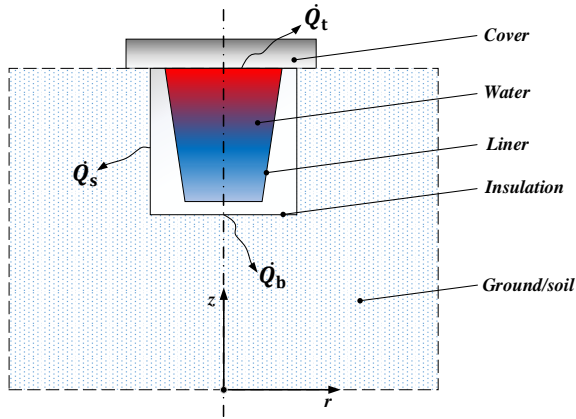
(b)	Case 1	Case 2	Case 3	Case 4	Case 5
Dam height, $h_{dam}$ [m]	15	15	15	15	15
Height, $h$ [m]	65	65	65	65	65
Diameter, $d$ [m]	44.3	62.6	99.0	140.0	197.9
Area, $A$ [m <sup>2</sup> ]	12115	18935	35594	59349	101957
Volume, $V$ [m <sup>3</sup> ]	100 000	200 000	500 000	1 000 000	2 000 000
$h/d$ [-]	1.469	1.038	0.657	0.464	0.328
$A/V$ [1/m]	0.121	0.095	0.071	0.059	0.051
Slope, $\alpha$ [°]	90	90	90	90	90

**Table 2** Shallow pit dimensions for the different volumes considered in this work. (a) low  $h/d$  shallow pit with 5 m dam and without dam. (b) high  $h/d$  shallow pit with optimised dam height and without dam.

(a)	Case 1	Case 2	Case 3	Case 4	Case 5
Dam height, $h_{dam}$ [m]	[0, 5]	[0, 5]	[0, 5]	[0, 5]	[0, 5]
Height, $h$ [m]	10.5	11.8	13.8	15.6	17.7
Top diameter, $d$ [m]	127.8	167	238.3	312.2	409.5
Bottom diameter,	91.4	126.2	190.5	258.1	348.1
Area, $A$ [m <sup>2</sup> ]	26620	45241	91669	156868	268997
Volume, $V$ [m <sup>3</sup> ]	100 000	200 000	500 000	1 000 000	2 000 000
$h/d$ [-]	0.096	0.08	0.064	0.055	0.047
$A/V$ [1/m]	0.266	0.266	0.183	0.157	0.134
Slope, $\alpha$ [°]	30	30	30	30	30

(b)	Case 1	Case 2	Case 3	Case 4	Case 5
Dam height, $h_{dam}$ [m]	[0, 5]	[0, 7]	[0, 8]	[0, 10]	[0, 15]
Height, $h$ [m]	12.0	15.0	20.0	25.0	30.0
Top diameter, $d$ [m]	122.5	154.1	217.9	265.0	339.6
Bottom diameter,	82.2	105.0	135.8	184.0	240.3
Area, $A$ [m <sup>2</sup> ]	24641	38996	77125	115272	188756
Volume, $V$ [m <sup>3</sup> ]	100 000	200 000	500 000	1 000 000	2 000 000
$h/d$ [-]	0.117	0.116	0.113	0.111	0.103
$A/V$ [1/m]	0.246	0.195	0.154	0.115	0.094
Slope, $\alpha$ [°]	30	30	30	30	30



**Figure 4** An exemplary 2-D sketch for representing an underground pit [8].

### 3.1 Model Implementation and Development

The analysed storage options (cylindrical tank and shallow pit) are symmetrical along z-axis (see

**Figure 4**), thus it is possible to simplify the geometry to a single half of the storage. This feature reduces significantly the computation efforts and yields no significant changes in results compared to a full storage model. The energy balance for a central volume element in the storage is given by the following equation:

$$(\rho A c_p) \frac{\partial T(t)}{\partial t} = -(\rho c_p \dot{V}_w) \nabla T + A \nabla \cdot (\lambda_w \nabla T) - U_{wall} \cdot (\pi d) \cdot (T(t) - T_{ground}(t)) \quad (1)$$

In the above equations,  $\rho$ ,  $c_p$  and  $\dot{V}_w$  stand for the density, specific heat capacity and volumetric flowrate of the fluid, respectively.  $U_{wall}$  is the overall heat transfer coefficient of the storage envelope (fluid to ground), whereas  $A$  is the cross section area of the corresponding segment. The material properties used in the simulations are presented in **Table 3**.

It is important to mention that when the simulation reaches the upper layer (1<sup>st</sup> layer in the tank), another heat loss term ( $\dot{Q}_t$ ) is accounted for and, therefore,  $A_{top}$  is used to include the upper surface area of the first segment in calculations. The same applies when the calculation reaches the last layer in the storage model; thereby, the heat loss from the bottom ( $\dot{Q}_b$ ) is included.

The presence of buoyancy driven heat flow, which is a characteristic of water-based storage systems, is introduced with an enhanced water thermal conductivity value to account for the additional mixing in presence of negative vertical temperature gradients. The implementation of this additional term is extensively presented in [8] and [11].

As the storage is buried in the ground, the heat losses from the lateral and bottom areas of the storage find their way to the ground. Thus, a conductive heat transfer takes place and obeys the following equation:

$$(\rho_g c_{p,g}) \frac{\partial T_g(t)}{\partial t} = \nabla \cdot \dot{q} \quad (2)$$

The presence of groundwater (GW) is also an important factor that needs to be considered in the planning of a TES. In particular, the twofold influence between TES and GW has an influence not only on the TES efficiency (the flowing of GW increases the thermal losses) but also on the groundwater itself, which sees an increase in its temperature [12]. In the simulations results presented in the following paragraphs, the influence of GW is neglected, in order to present a general overview of the possible technical TES designs. However, the costs related to the possible geotechnical measures (i.e. thermal insulation and cut-off wall [12]) to tackle the impact of GW are not negligible and are therefore included in the cost evaluation.

**Table 3** Properties of the materials and overall heat transfer coefficients (HTC).

Parameter	Value
Water thermal conductivity, $\lambda_w$	0.6 W/(m K)
Water density, $\rho$	1000 kg/m <sup>3</sup>
Water specific heat capacity, $c_p$	4200 J/(kg K)
Overall HTC of the cover, $U_{cover}$	0.1 W/(m <sup>2</sup> K)
Overall HTC of the wall, $U_{wall}$	0.3 W/(m <sup>2</sup> K)
Overall HTC of the bottom, $U_{bottom}$	0.3 W/(m <sup>2</sup> K)
Ground thermal conductivity, $\lambda_g$	1.5 W/(m K)
Ground specific heat capacity, $c_{p,g}$	880 J/(kg K)
Ground density, $\rho_g$	1000 kg/m <sup>3</sup>

### 3.2 Techno-Economic Analysis

The main performance indicator is the efficiency of a TES, which correlates annual thermal losses to the maximum theoretical storage capacity and expressed as below:

$$\eta_{sto} = 1 - \frac{Q_{loss}}{Q_{sto}} \quad (4)$$

The storage losses depend on the operation and boundary conditions and are determined by dynamic thermal simulations. The storage capacity is a function of the TES volume, the storage medium and the maximum and minimum temperature:



$$Q_{sto} = V \cdot \rho \cdot c_p \cdot \Delta T \quad (5)$$

There exist some other definitions for the storage efficiency and they are well reported in the literature [13]. In this work, however, the suitability of the chosen definition (Equation (4)) is observed since it compares the overall thermal losses to the maximum storage capacity, so it pinpoints the effective volume of the storage as follows:

$$V_{eff} = V_{sto} \cdot \eta_{sto} \quad (6)$$

Another reason is that this definition of the TES efficiency is less sensitive to TES operation parameters (e.g. charging/discharging). However, it has to be noted, that other performance indicators such as stratification number etc. should be employed in a more detailed study. Eventually, the primary energy savings (or reduction of CO<sub>2</sub>-emissions) are the overlaying goal.

For the economic analysis of TES construction, the total investment cost is calculated considering the different contributions of the materials, the facilities and the operations. Such contributions include earthworks, special geotechnical works (i.e. diaphragm walls, anchors, cut-off wall), insulation, liners, cover, plant construction and site facilities. **Table 4** reports a rough estimate of costs based on

experience gained through the *giga\_TES* project that can be used to elaborate trends, but are still subject to high uncertainty. Within the project, a cost tool for the evaluation and comparison of the investment costs of different TES sizes and designs was implemented [10]. This tool allows a detailed evaluation of the influence of the different cost items (i.e. earthworks, civil engineering works, envelope, cover, site costs and facilities). However, it is important to mention that it represents the current state-of-the-art of the presented geotechnical solutions and not the technological improvement and the research of more efficient procedures (i.e. for insulation and liner installation) that can lead to a substantial reduction of the currently suggested costs, which therefore represent a high bound of the cost range.

Compared to the costs presented in [8], the earthworks costs are further separated in excavation costs and costs required to build the embankment dam and to remove the unused excavated material. The costs related to the earthworks cover an important share of the investment costs. The transportation and disposal of the excavated material is a game changer in case of high TES volumes, therefore it is recommended, when possible, to use part of the excavated material to build an embankment dam that

**Table 4** Different specific costs for the construction of high temperature seasonal TES (adapted from [8]).

Contribution		(Specific) Costs	Remark
Earthworks	excavation	1.5 - 7 €/m <sup>3</sup>	dependent on the excavation depth
	dam construction	5 €/m <sup>3</sup>	refilling of excavated material
	removal of excavated material	13 €/m <sup>3</sup>	transportation and disposal
Diaphragm wall		625 - 475 €/m <sup>2</sup>	dependent on the depth
Retaining anchors		5000 €/anchor	Required in case of vertical walls with diameters over 100 m
Cut-off wall		50 €/m <sup>2</sup>	In case of ground water in 5 m distance
Insulation		100 €/m <sup>3</sup> 200 - 300 €/m <sup>3</sup>	Bottom (pressure resistant) Wall (including installation)
Liner		150 - 300 €/m <sup>2</sup> 50 €/m <sup>2</sup>	VA, Stainless steel (HT) Polymer liner (LT)
Cover		200 €/m <sup>2</sup> 950 €/m <sup>2</sup>	Floating cover (50 cm ins.) Trafficable floating cover
Plant construction		0.4 €/m <sup>3</sup>	dependent on the TES volume
Site facilities		10 % of earthworks – 10 % of total costs	

would allow to reduce the total excavation depth and the amount of material that needs to be disposed. This solution is however not always possible if the storage is to be built in an urban area.

Under the given TES excavation depth (e.g. 50 m for 100 000 m<sup>3</sup> tank), diaphragm walls are perfectly suited for the construction of cylindrical tanks. However, when increasing volumes and diameters, the use of retaining anchors in the tank TES geometry is recommended in order to absorb the earth pressure during the construction stage. The installation of a cut-off wall is necessary in presence of GW, in order to limit the GW overheating [12]. The use of reinforced concrete is another cost item highly dependent on the TES geometry and size and on the selected civil engineering solutions.

When it comes to the liner cost, it is important to differentiate between liners applicable for low temperature (LT) and high temperature (HT) systems and to consider different service life times. For TES in HT systems the liner is made of stainless steel (VA), whilst polymer liners are applicable for LT systems. Since this work considers the implementation of a HT TES, the cost analysis will consider the application of a VA liner, since it is currently the recommended solutions in presence of high temperatures. However, there are currently under study promising developments for increasing the life of polymer liners [14]. The costs estimation related to the VA liner installation is still subject to large uncertainty related to the type of TES geometry.

Thermal insulation is a critical element of the TES for its role in improving the TES efficiency and reducing the impact on the surrounding ground but also for its cost. The current TES systems in Denmark do not have a lateral insulation, but only an insulated floating cover [15]. Therefore, the costs associated to the insulation (i.e. material and installation) are still very uncertain: the technology development in the next years can lead to a substantial reduction of the costs. Moreover, the insulation applied on the storage bottom should be able to provide pressure resistance but is exposed to lower temperatures than the wall insulation. The insulation of the TES cover is in any case strongly recommended since it is the envelope element with the highest specific thermal losses. The high cost variation for the cover presented in the table are related to its accessibility: a floating cover is cheaper, however, in case of installation in urban areas, the usability of the surface is an important advantage but would require a more expensive trafficable solution.

The cost of the site facilities presents also an important variation depending on the TES size, geometry and on its features (i.e. dam, insulation, GW presence), therefore the costs estimations presented in the following paragraph will account for the range presented in **Table 4**. Another important aspect that should be taken into account is the land cost; the land prices of an urban area are significantly higher than those of an industrial or agricultural area, thus introducing another element of uncertainty in the estimation of a general indication of the investment costs.

For the economic analysis, according to the theory of investment it is possible to represent an investment with annual fixed payments. Assuming a service life of  $n = 50$  years and a discount rate of  $i = 3\%$  the annuity factor  $ANF$ , defined in Equation (7),

$$ANF_{n,i} = \frac{(1+i)^n \cdot i}{(1+i)^n - 1} \quad (7)$$

is 3.9 % [8]. 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. For example, if instead of a stainless steel (VA) liner a polymer liner is used with a lifetime of say  $n = 20$  years, the  $ANF$  is 6.7 % (compared to 3.9 % for 50 years). Considering the above given capital cost of 150 €/m<sup>2</sup> for the VA liner and 50 €/m<sup>2</sup> for the polymer liner, respectively, it becomes obvious that in spite of the longer service life of VA compared to polymer liner, the latter has the better economic performance (3.35 €/m<sup>2</sup>/a compared to 5.85 €/m<sup>2</sup>/a). However, if in addition to the replacement of the liner some other components (such as the insulation or the cover) have to be replaced, the situation is different and the VA liner outperforms the polymer liner.

## 4. RESULTS AND DISCUSSION

Dynamic TES simulations were presumed to start on May 1<sup>st</sup> of each simulation year. The charging phase starts and lasts over a course of three months during which the storage is injected with excess heat (e.g. solar energy) collected by means of hot water. This phase is followed by a three months storage phase. Next, the discharging phase takes place followed by a three 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, anyway shorter timespan did not provide significant changes in



results. The results presented in the following paragraph are extracted from [8].

#### 4.1 Impact of District Heating Temperature

The charging/discharging characteristics (i.e. temperature, flowrates) play an important role in TES operation. In this context, it is held that one of the key goals for future DH systems is lowering the supply/return temperatures in order to achieve higher system performance. Therefore, this section compares TES operation in LT and HT DH systems. To provide a peer-to-peer comparison, the boundary conditions are kept the same. This means the temperatures are set to (80 °C/ 30 °C) in a LT system producing a lower flowrate to ensure the same energy injected into TES during charging/discharging processes, while in a HT system the flow and return temperature are 90 °C, and 60 °C, respectively.

The resulting storage efficiency is presented in **Figure 5** for both the cases with and without insulation for the tank TES with a total height of 50 m. For a storage volume of 100 000 m<sup>3</sup>, better STES performance was found for LT DH systems compared to HT DH systems for the similar boundary conditions. This is because the low supply and return temperatures result in lower thermal losses.

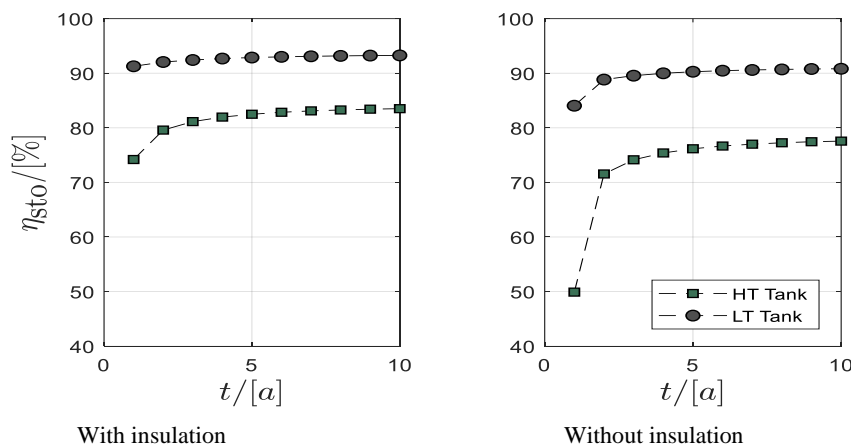
Another important case is the storage performance when no insulation encloses the storage, since this represents the current state-of-the-art of the large pit TES in Denmark [15]. **Figure 5(b)** shows the evolution of storage performance over the course of 10 years and it reveals that the tank performance starts with poor performance of around 50 % in case of HT DH systems. Later, the performance starts to develop remarkably scoring 75 % in the 5<sup>th</sup> year. This

significant increase in storage performance (case no insulation) is strongly accredited to the ground preheating driven by the high lateral and bottom thermal losses in absence of insulation.

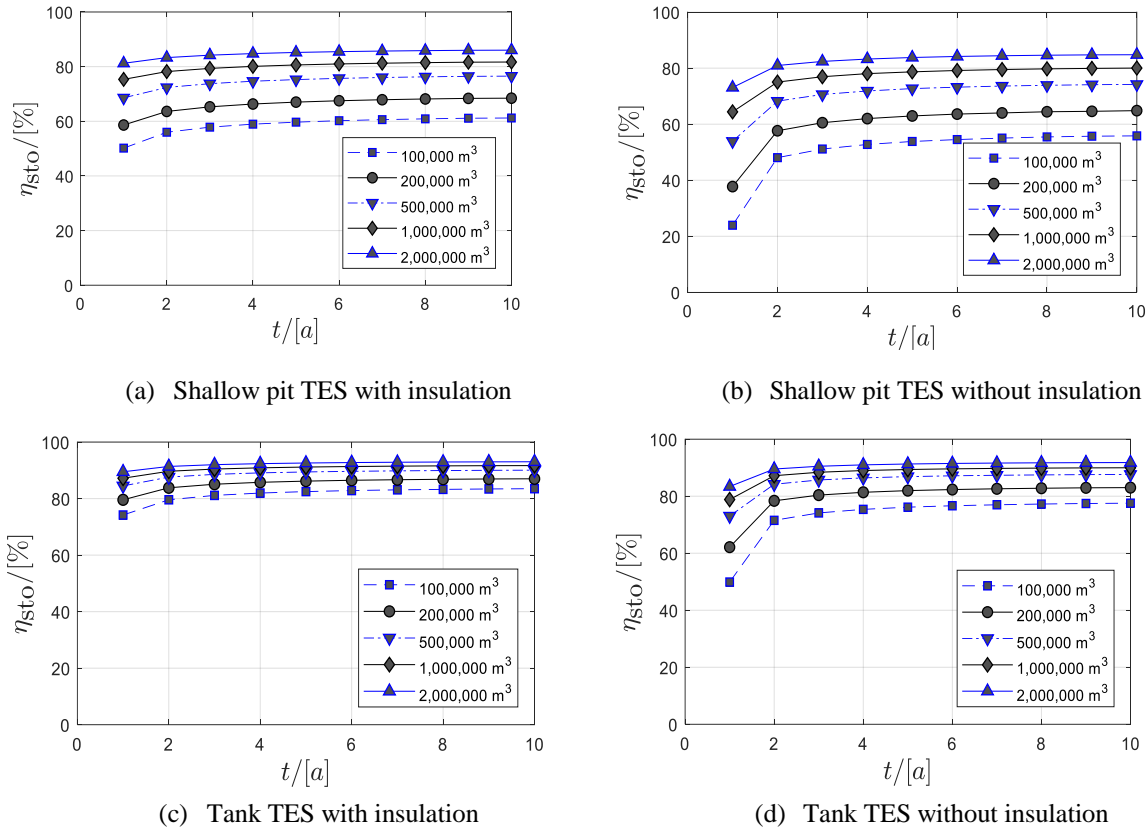
#### 4.2 Impact of Storage Volume

An important consideration in a large-scale seasonal TES system is the ratio of storage volume to surface area ( $A/V$ ), which has a direct impact to the external thermal losses from the storage. Therefore, it is recommended to maintain the surface area as minimal as possible and the volume as high as possible, i.e. ensure a small  $A/V$  ratio. In this section, a comparison for different volumes of different TES geometries is carried out. Additionally, the comparison includes two cases, fully insulated (“with insulation”) or only insulation at the cover (“no insulation”). **Figure 6** reveals the evolution of storage efficiency over a course of 10 years for the 50 m high tank TES (**Table 1(a)**) and the shallow pit with low  $h/d$  ratio (**Table 2(a)**). The impact of the embankment dam is here not considered.

Generally, the tank appears to outperform the shallow pit for both insulation cases. This indicates that the effective storage volume of the tank is higher than the one of the shallow pit for any considered total volume. **Figure 6(a)** and **Figure 6(b)** indicates the shallow pit performance under two cases (with and without insulation). Obviously, the shallow pit has better performance when the insulation encloses the storage. This is, however, true only for volumes ranging between 100 000 m<sup>3</sup> and 500 000 m<sup>3</sup>.



**Figure 5** Evolution of tank performance over a time span of 10 years of operation in LT and HT DH systems for two cases: (a) with insulation, and (b) without insulation (ground thermal conductivity  $\lambda_g = 1.5 \text{ W/(m}\cdot\text{K)}$ ) [8].



**Figure 6** Evolution of tank performance over a time span of 10 years of operation in HT DH systems for two cases (with and without insulation) and two TES geometries (tank and shallow pit). Each with a ground thermal conductivity  $\lambda_g = 1.5 \text{ W/(m}\cdot\text{K)}$  [8].

For higher volumes, the storage performance is seen similar for both cases despite the difference seen during TES start-up phase. This means that the insulation plays a major role only to prevent a severe overheating of the surroundings since the shallow pit ends up with a similar performance after 10 years. In the case of the shallow pit the major contribution of losses comes from the top surface area due to the large diameters. Compared to the shallow pit, the tank is characterized by less thermal energy losses to the surroundings through its lateral area. However, exceeding a volume of 500 000 m<sup>3</sup> while maintaining same height (in this work, 50 meters) will yield higher portions of energy lost through the top surface area compared to other contributions (bottom and lateral) [8]. Therefore, it is important to underline the role of the aspect ratio ( $h/d$ ) when dimensioning a seasonal TES. Frequently, an aspect ratio of 1 is seen the most promising for better performance. Nevertheless, due to some technical challenges during construction, STES systems with aspect ratios less than one are often realized. Compared to the tank, the high top thermal losses in case of shallow pit are strongly attributed to

the poor  $h/d$  ratios given for the shallow pit as depicted in **Table 2**.

The aforementioned results confirm the importance of maintaining an  $A/V$  ratio as minimal as possible in order to reduce the magnitude of external thermal losses. By recalling ( $A/V$ ) it is inevitably realized that the tank configuration has better ratios over those of the shallow pit. Therefore, the tank outperforms the shallow pit.

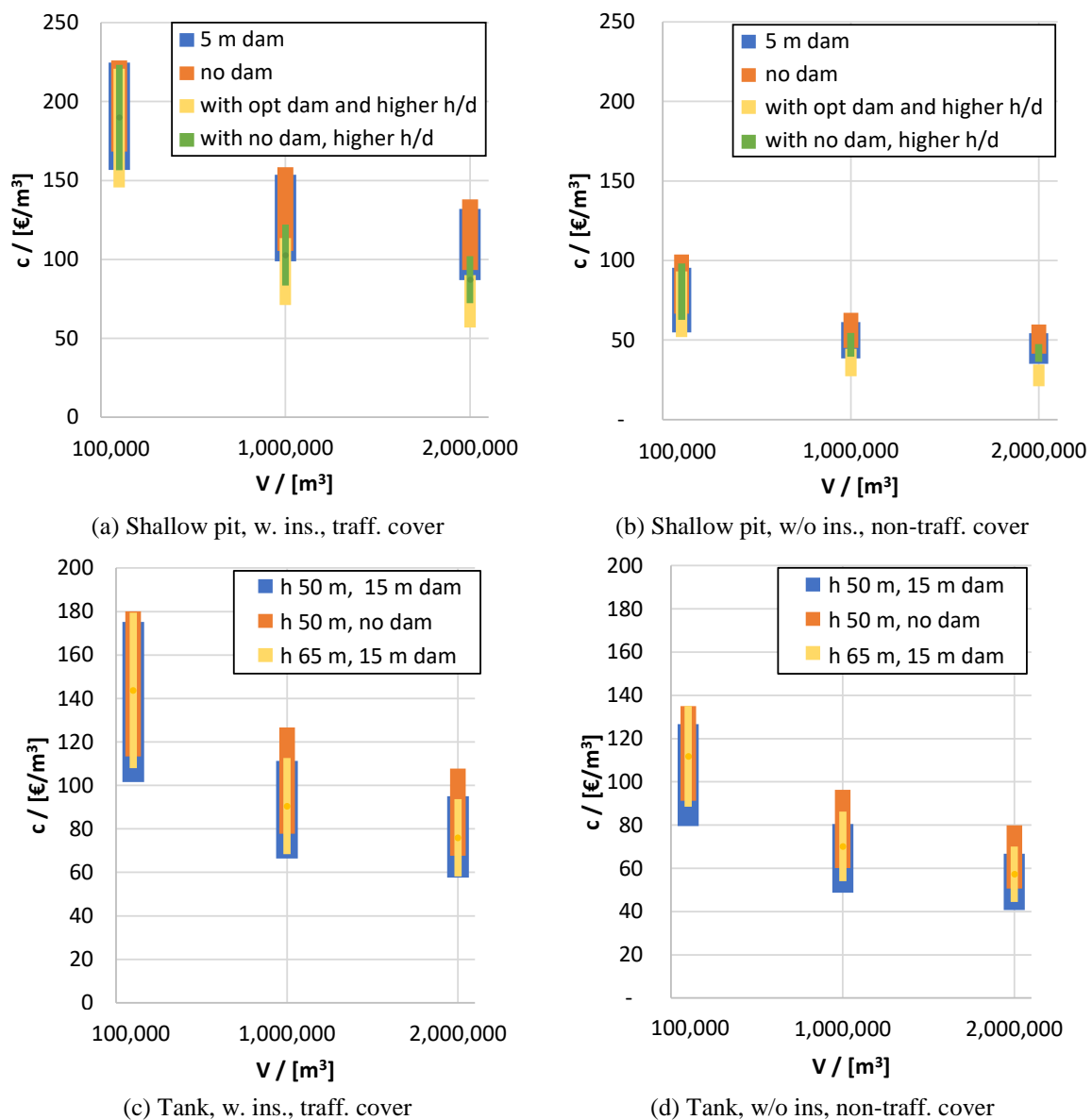
Moreover, the low performance during the first years (TES start-up) implies high thermal losses to the surroundings (e.g. the ground) resulting in higher ground temperature. These results highlight the importance of insulation, which is under these circumstances installed only to protect the ground and the quality of GW.

### 4.3 Cost Estimation

**Figure 7** shows the cost range for various TES configurations: (a) a shallow pit with insulation and trafficable cover, (b) a shallow pit with no insulation and non-trafficable cover, (c) a tank with insulation

and trafficable cover, (d) a tank with no insulation and non-trafficable cover. The geometry configurations presented (4 for the shallow pit and 3 for the tank) are those presented in **Table 1** and **Table 2**. The upper range considers the currently standard available costs in terms of geotechnical and civil engineering solutions and envelope installation and the location of the TES in an urban area (upper limit of **Table 4**). Whereas, the lower range considers the most optimistic design conditions and price development as from **Table 4**, and negligible land costs. Considering the high temperatures involved, the use of VA liner is assumed.

It is possible to see that the most expensive solution is represented by the insulated shallow pit with trafficable cover (a), while the shallow pit with standard floating cover and no lateral insulation (b) represents the most cost-effective. However, the range of costs for each solution is very wide and forces the planner to deeply investigate the single cost items and location requirements before restricting the choice to one specific geometry. For example, if the use of a trafficable cover is required, the use of a tank TES is recommended, rather than a shallow pit, since the lower cover surface allows to reduce the associated costs and the land use. It is nevertheless possible to



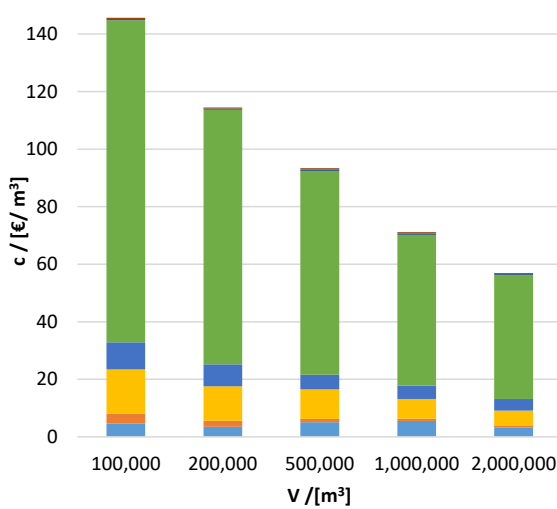
**Figure 7** Cost range for shallow pit and tank TES systems in different configurations and with different volumes.

identify a decreasing trend of the specific costs with increasing volume size; the use of a larger TES would result in lower specific costs, but a small variation would imply a significant increase in the total investment costs.

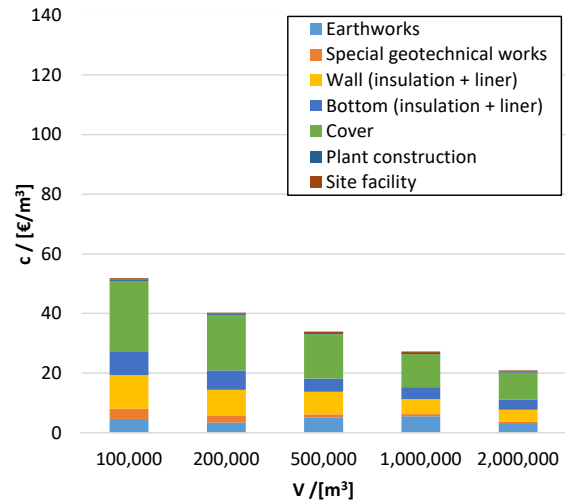
From **Figure 7** it is also possible to see that for the shallow pit, the use of an optimised dam height (balanced with the excavated volume) allows to reduce the costs compared to the case with no dam, when all the extracted material needs to be disposed. This

distinction is present also in the case of the tank TES geometry, although the impact is less evident.

**Figure 8** and **Figure 9** show the contribution of each specific category in TES construction and implementation (referred to the lower bound of **Figure 7**) of the total specific cost. The geometry configurations presented are the ones that present the minimum cost range in **Figure 7**, namely the shallow pit with optimised dam height and high  $h/d$  and the 50 m deep tank with 15 m dam. It is clearly highlighted

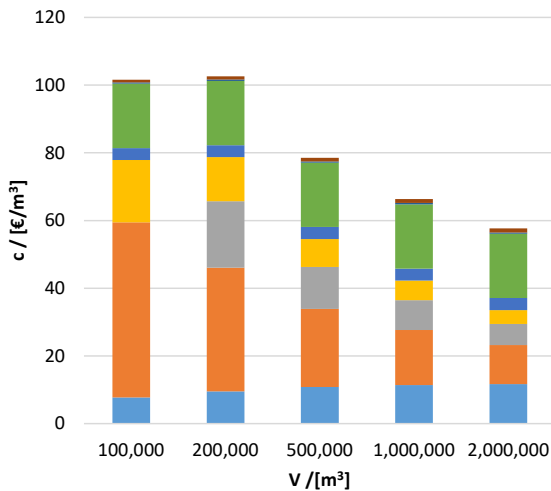


(a) Shallow pit, w. ins., traff. cover, opt.  $h$  and dam

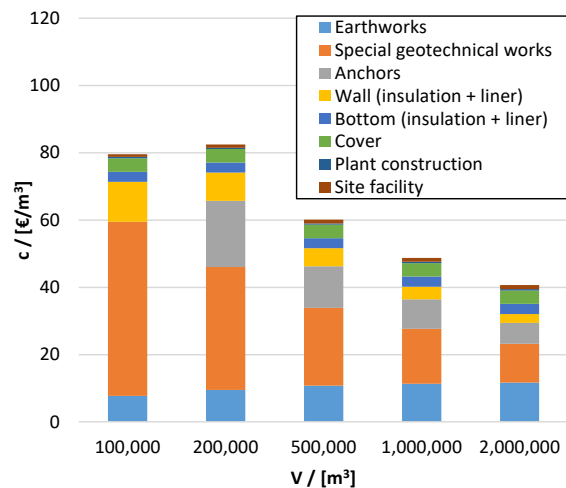


(b) Shallow pit, w/o ins., non-traff. cover, opt.  $h$  and dam

**Figure 8** Breakdown of the total specific costs (low range of **Figure 7**) for shallow pit TES with different volumes and envelope conditions.



(a) Tank, w. ins., traff. cover, H 50 m, 15 m dam



(b) Tank, w/o ins., non traff. cover, H 50 m, 15 m dam

**Figure 9** Breakdown of the total specific costs (low range of **Figure 7**) for tank TES with different volumes and envelope conditions.

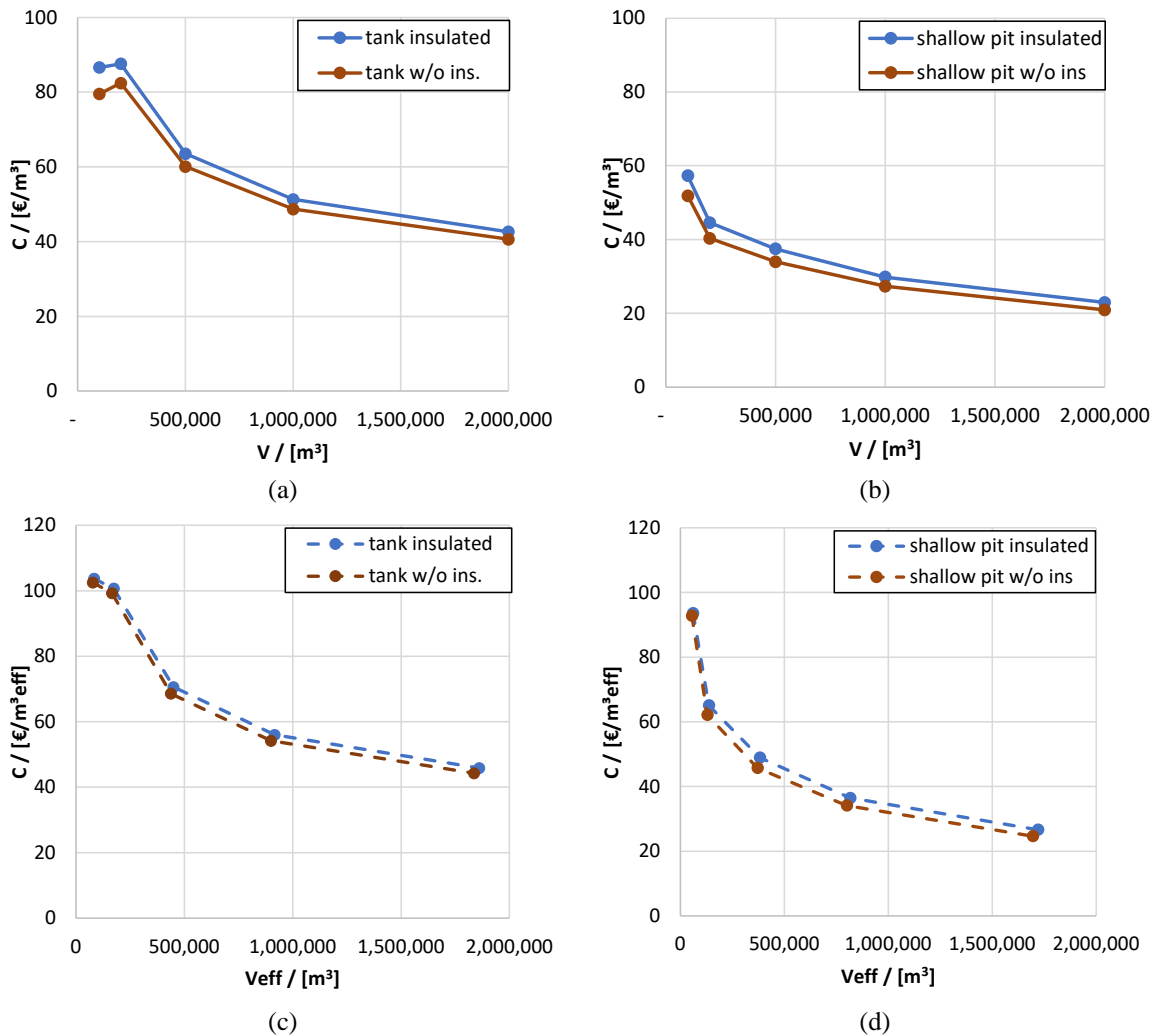
that the special geotechnical works (defining the diaphragm wall and the cut-off wall) and the anchors have a major contribution in case of tank. This contribution tends to decrease with increasing storage volume until it becomes slightly smaller compared to the cost of the cover and the earthworks in large volumes (e.g. 1 000 000 m<sup>3</sup> to 2 000 000 m<sup>3</sup>). Whereas the cover contribution plays the major role in the total specific cost of the shallow pit and its influence tends to decrease while increasing TES volume. However, it remains the major contribution.

In order to compare different construction types and geometries, it has to be taken into account that the performance of the TES depends strongly on the choice of the geometry, level of insulation and many other parameters. Eventually, this can only be done in the context of the DH system. However, at least by trend, conclusions can be derived, if instead of the total TES volume, the effective TES volume is used (see

Equation (5)). From **Figure 10** it can be seen that if the effective volume is used for the calculation of the specific costs, then the difference between the insulated and non-insulated TES reduces. Hence, one of the main goals should be the development of materials and technologies to achieve cost effective methods to apply insulation of TES.

## 5. CONCLUSIONS

In DH systems, large-scale thermal energy storage offer a great potential to enhance the flexibility and maximize the use of renewables and, thus, TES reduces the fossil fuels use. Having concerned the various aspects of heat demand/supply flexibility, the dispatchability of renewables and the potential for sector coupling with electricity networks, large-scale TES will be strategic for the DH network and the energy system. This work developed and discussed the



**Figure 10** Specific cost for the tank (a, c) and for the shallow pit (b, d) related to the volume (a, b) and related to the effective volume (c, d).

techno-economic evaluation of large-scale TES concerning different aspects (DH characteristics, type of construction, geometry, insulation, type of cover) and for different TES volumes. However, it is important to note that all results presented apply for a case with a ground thermal conductivity of 1.5 W/(m·K) and without significant groundwater flow.

The work also depicted that increasing the storage volume reduces the difference in storage performance between different TES configurations (in this work: with and without insulation). Still, the tank showed better performance compared to the shallow pit for the volumes considered here. However, modifying the TES geometry and installing the insulation can involve different conflicting objectives for the overall cost reduction. The reason is that, on one hand, it is necessary to reduce the capital cost. Whereas on the other, it is desired to have TES with performance as maximal as possible and most of all, to limit the overheating of the ground in presence of groundwater.

The work showed that investing in enclosing the tank with insulation seems to be more feasible and practical than in the shallow pit case. Additionally, investing in trafficable cover for the shallow pit maximizes enormously the total capital cost. Consequently, if the usability of TES cover is needed and a must, then it is important to highlight the higher economic feasibility and the greater technical potential of the tank over the shallow pit. Otherwise, if a trafficable cover is not required, then the shallow pit has lower capital costs compared to tank.

The wide range of the specific costs for the analysed TES cases highlight the high importance of research and development of cost-optimal solutions for the installation of liners and thermal insulation alongside the optimisation of the geotechnical work. The reduction of the investment costs is a key-factor to ensure a wide application of this technology.

Moreover, this work presented a different performance indicator (Equation (4)) to what is actually used in the literature. This is because of the applicability of this indicator to compute the storage effective volume. For a comparison of different TES types it is important to utilize the effective volume for the economic calculation instead of the total volume and it can be seen that the difference of the specific costs between insulated and non-insulated almost vanishes.

Furthermore, there is still work to be done regarding the further development of numerical models, their validation and the assessment methodology for techno-economic analysis. There

exist many challenges that require further investigation to identify the toughest barriers and to tackle them properly in order to develop and market the seasonal TES.

## AUTHORS' CONTRIBUTIONS

**Alice Tosatto:** Data collection and analysis, Scientific support, Writing – original draft. **Fabian Ochs:** Conceptualisation, Methodology, Scientific support, Writing – original draft. **Abdulrahman Dahash:** Conceptualisation, Software, Data collection and analysis, Scientific support, Writing – original draft. **Christoph Muser:** Economic evaluation, Insights on construction techniques, Writing – review.

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