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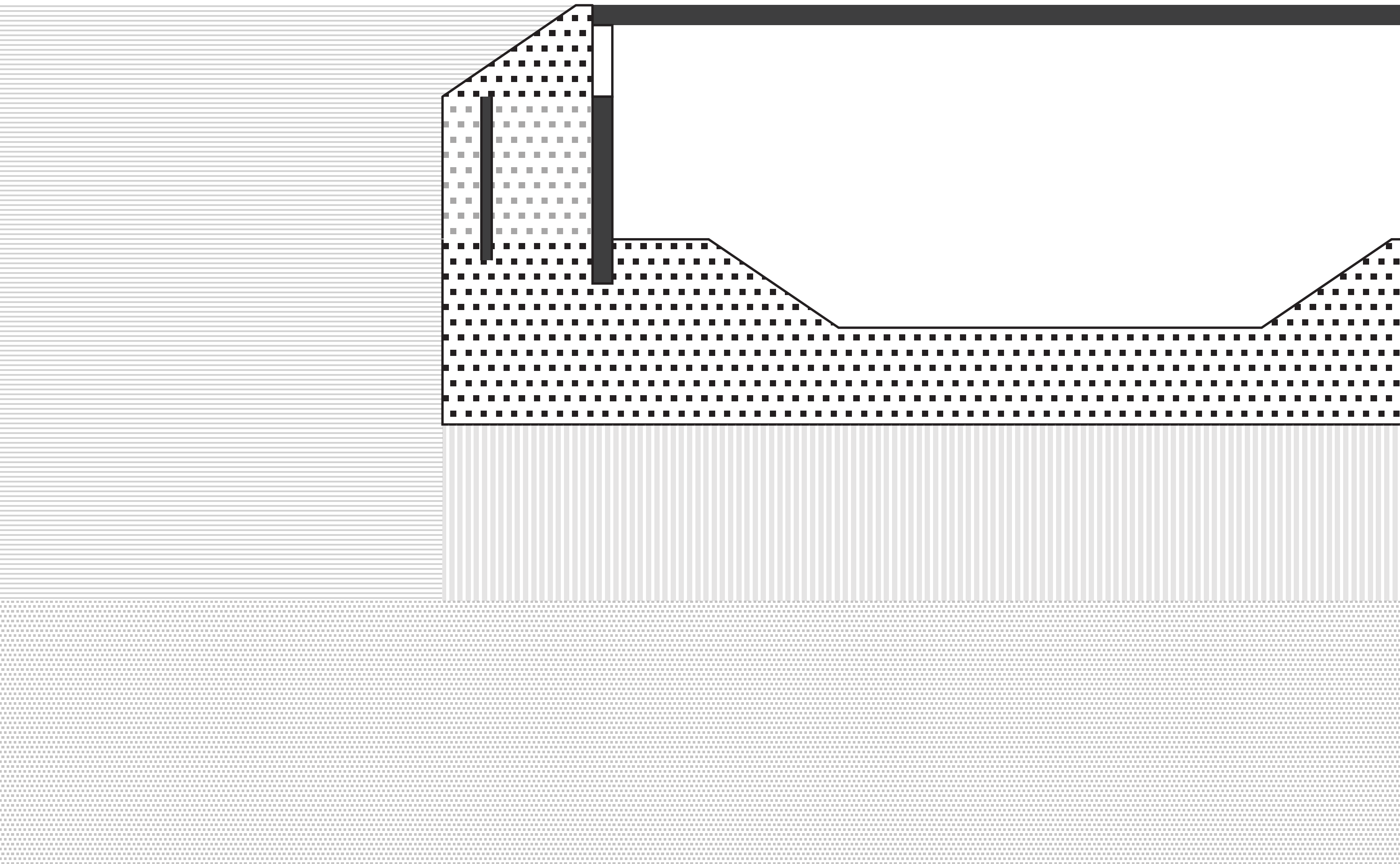
Giga-scale thermal energy storage for renewable districts



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Giga-scale thermal energy storage for renewable districts

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Executive summary

Bridging from summer to winter and adding flexibility to district heating networks, so that they can utilise more renewable heat sources and more heat from renewable energy driven conversion technologies. That is the aim of large thermal energy storages. These technologies are still in their early stages, with the largest storages now in practice in Denmark, enabling seasonal thermal energy storage (TES) and adding electricity grid flexibility through power-to-heat technologies. Large thermal energy storages (LTES) in district heating systems are a necessary addition in order to reach the long-term goal for a one hundred percent renewable energy system.

The challenge for the 3-year gigaTES flagship project, funded by the Austrian Climate and Energy Fund[1], was to develop materials and building concepts, evaluate the LTES performance and its interaction with the environment as well as to investigate integration possibilities of LTES in district heating systems throughout Austria. This was done with a broad group of industries from all parts of the value chain for large thermal energy storages, together with research institutes from Austria and from abroad. The target was to have all of these elements in place for a next step: a first demonstration of the new technology.
The already existing large thermal energy storages, located mainly in Denmark, formed the basis for the development work, and with specific investment cost levels of as low as 30 € per cubic meter of water equivalent, proved to be a very challenging baseline to improve on. This is even harder as the boundary conditions in Austria are stricter: in an urban environment, large volumes of storage can only be realised when deep constructions are being made in order to minimise the required land use. Then, the concepts have to deal with hydrogeological challenges such as groundwater flow and groundwater quality regulations, making thermal insulation or shielding from the groundwater necessary, driving up the costs.

These strict boundary conditions have been addressed within the newly developed gigaTES building concepts. A new patented method to add a thermally insulating underground ring around the storage was devised and tested on a small scale. As for the very important cover, that, through the required combination of thermal insulation, water tightness, water vapour tightness and load bearing capacity, is the most expensive component, two new, patented concepts were developed that enable additional use of the expensive storage cover top surface.

On a materials development level, a novel polymer for the liner was developed and dedicated tests showed that we can expect a doubling of lifetime under higher temperature conditions compared to existing polymer liner materials.
The project also developed a series of numerical simulation tools that enable to optimise the functioning and integration of the storage. Parameters that can be optimised are the interaction of the thermal energy storage with the surrounding soil and with the groundwater flow, the influence of different concepts for thermal insulation both inside and outside of the storage, the thermodynamic behaviour of the water in the storage and thus the storage efficiency and the dynamic, multi-annual interaction of the storage with the district heating system.

[1] Project 860949, funded by the FFG under the Energy Research Programme, 3rd Submission.

The planning, design and building of a large thermal energy storage is restricted by a large number of boundary conditions and influencing factors. These conditions were gathered and together with the aspects that should be taken into account when commissioning and operating the storage form a very practical guideline for those thinking about the realisation of a large thermal storage in a district heating system.

The modelling of the system performance of the storage was combined with a building cost tool, that holds the costs of all components, materials and building processes taken from present deep construction experience, to enable a cost optimisation of the large thermal energy storage in a given district heating system. In this report, two case studies are outlined for a techno-economic analysis and the resulting levelized cost of storage are already on a good level but not as low as the presently existing large TES in Denmark. This is understandable, as the requirements to the storage in Central-European conditions are relatively high.

The target of the gigaTES project was to enable the demonstration of a large thermal energy storage for district heating in Austria. This aim was achieved. We have developed sufficient knowledge to plan, design and test this storage and its integration into larger systems. The challenge is to find an optimum between the risks of a demonstration and the cost of a large thermal energy storage. The demonstration would need to give answers to questions that were generated in the project: what are the best and most cost-effective construction methods for the designed gigaTES concepts? What is the long-term mechanical behaviour of a gigaTES storage in the underground? What are the best construction methods for vertical wall liners? How do the newly developed materials behave in practice? These questions are best addressed in one or more smaller demonstration projects. With these, valuable practical experience will also be gained that will help to drive down the risks and costs of consecutive generations of larger thermal storages.

Also internationally, the gigaTES project has set a new mark for the development of large thermal energy storages. Plans are being developed in a number of countries, for instance Denmark, Germany, The Netherlands and Poland and the developments would definitely benefit from and being accelerated by a concerted European collaboration. Moreover, the higher European goals for CO_2 emission reduction have increased the necessity for a swift introduction of more renewable heat sources in combination with thermal energy storages, also in large systems. Therefore, the outlook is that the coming years will see a number of novel demonstration projects, novel concepts and integration methods as well as novel tools and equipment for large thermal energy storages.

1 Introduction

In the 100% renewable energy society that we are realising, a large part of the renewable energy sources is of a varying nature. This also holds for the renewable heat sources, that are put to work to supply all our houses, offices and industries with hot water, space heating, industrial heat and cold. This only works if the energy system is equipped with storage technologies, bridging the gap between supply and demand on short-, medium- and long-term timeframes and increasing sector flexibility by enabling sector coupling. Small heating networks need small thermal storages, big ones need big. While present storages have volumes up to 200.000 cubic meters, medium to large cities will need storages with volumes up to a few million cubic meters. Present large thermal storages all use water as the storage medium; and this is the widest applied technology, because of its simplicity and low cost. The bulk of the existing large thermal energy storage have been realised in Denmark, coupled mostly to community district heating systems. With fairly deep groundwater levels and soils composed mostly of sand or light ground in combination with rather cheap land prices, Danish storages can be realised with relatively low cost.

This is different in Austria and Central Europe in general. Here, shallow groundwater levels, more demanding soil composition and district heating systems in more densely populated areas with high land prices call for novel building and materials solutions for large thermal energy storages.

The experience with Danish and German storage projects provided the main R&D questions for the consortium. In order to keep the cost of the storages low, the operation temperature range should be higher and the land area needed should be minimised, while heat losses and influence on ground water temperature should be kept to a minimum. As such, liner materials that can withstand higher storage temperatures and have longer lifetimes are needed, deep underground construction concepts with thermal insulation functionality are to be developed, together with concepts for the lid that are water and water vapour tight, well insulated, and strong enough to enable profitable use of the cover area. Furthermore, the integration of the large thermal energy storage in the urban environment and in the district heating system should be done optimally and adequate tools should be available to optimise concepts, performance and cost.

From these R&D questions the main targets of the gigaTES were formulated: to generate novel building concepts, develop new materials, determine the boundary conditions that technically and economically influence the storage concept and its performance in a district heating system and to numerically simulate the performance of constructions, of the storage itself, its surroundings and of district heating systems equipped with the storage. These targets all make up the overarching goal to enable the introduction of large thermal energy storages in Austrian district heating systems as well as to stimulate the development in Europe.

The gigaTES project team consisted of 18 organisations from industry, R&D and district heating, who together covered the complete value chain for planning, building, integrating and operating large thermal energy storages.

With this publication, the outcomes of the gigaTES project are described in a concise manner. With it, all those confronting the challenges of how to implement a large thermal energy storage in a district heating system can find first directions on possible concepts, materials, integration possibilities, performance and costs. To this end, the publication is structured as follows.

First, technologies for storing large quantities of heat are introduced and large thermal energy storages and their integration possibilities as well as boundary conditions for an effective design and implementation are given in **Chapter 2**. In **Chapter** 3, a description is given of the building concepts for an LTES in Austrian conditions, that were developed in the gigaTES project. Then, in **Chapter 4**, the basis for choosing a proper storage concept for two case studies is described, including the method to evaluate and analyse the techno-economic performance.

In the project, a cost calculation tool was developed. This tool is used to determine the cost estimates for various storage design concepts for a given application. How this can be done for the two exemplary case studies is described in **Chapter 5** as well as a detailed breakdown of the overall techno-economic performance of both case studies. Going into more scientific detail, the materials developments in the project are described in **Chapter 6**, and the application of numerical simulation tools developed in the project to determine the influence of a number of design parameters on the performance of a LTES is explained in **Chapter 7**. **Chapter 8** then gives a description of the aspects that are important when commissioning and operating a LTES, regarding start-up, monitoring, and maintenance.

2 Large thermal energy storages - LTES

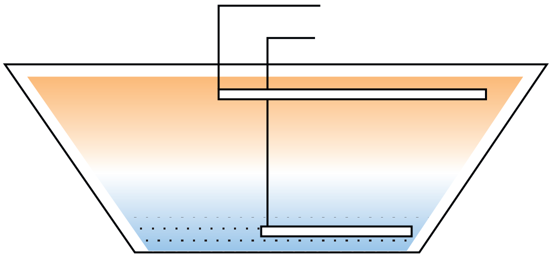
Thermal storage as part of district heating networks is a proven solution for bridging the temporal shift between supply and demand and can make a significant contribution to increasing renewables in district heating networks in the future. While smaller-scale solutions – both in terms of thermal capacity as well as in temporal shift – are widely applied, large thermal energy storage systems are still scarce. In addition to seasonal heat storage of, for example, solar thermal energy, large storages may operate either as seasonal, short-term or multi-functional heat storage systems that enable flexible heat storage of a wide variety of heat sources, such as industrial waste heat, geothermal and power-to-heat concepts. A successful development of widely applicable large thermal storage concepts and a later roll-out is a vital element of our future heat supply.

Please note that we will use the abbreviation **LTES** -large thermal energy storage- in this publication for the storage concepts developed in the project, being partly underground pit thermal energy storages or underground tank thermal energy storages or combinations of these.

2.1 Large thermal storages and markets for DH

Seasonal thermal energy storages (TES) for district heating systems have been investigated for the past 35 years. Four basic types of large, seasonal TES exist: Pit Thermal Energy Storage (PTES), Tank Thermal Energy Storage (TTES), Borehole Thermal Energy Storage (BTES) and Aquifer Thermal Energy Storage (ATES), as shown with their advantages and disadvantages in Table 1. The decision for a certain concept strongly depends on the local boundary conditions given by geological and hydrological conditions of the respective location and by the individual district heating system as well as the temperature levels. While PTES (in Denmark) and especially TTES are becoming state-of-the-art for district heating application, the application of deep ATES is not widely implemented so far. In the last decade, large pit thermal energy storage became economically and technically feasible in Denmark [1] and [2].

Table 1: Overview pro's and con's of large-scale thermal energy storage technologies [3]



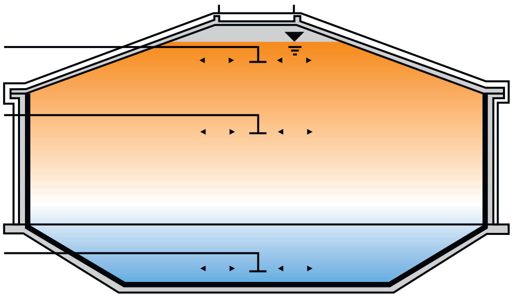
Pit Thermal Energy Storage (PTES)

+ acceptable construction costs
+ medium (gravel-water) to high (water) thermal capacity
+ almost unlimited size
+ thermal stratification

(+) operating characteristics (medium charge/discharge capacity for gravel-water)

(-) complicated and expensive cover for water

- limited freedom in design (slope angle)
- maintenance/repair difficult or not possible



Tank Storage (TTES)

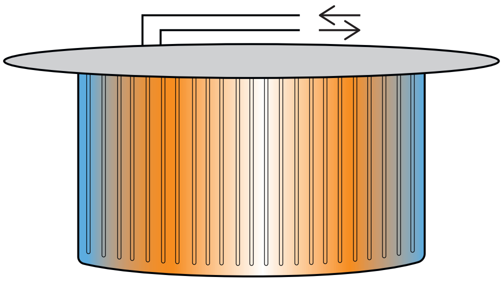
+ high thermal capacity (water)
+ good operating characteristics (high charge/discharge capacity, can be used as buffer storage)
+ freedom in design (geometry)
+ thermal stratification

(+) maintenance/repair

(-) limited size (< 100.000 m^3)

(-) primary energy demand

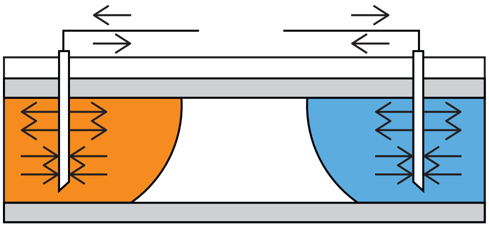
- high construction costs



Borehole Thermal Energy Storage (BTES)

+ low construction costs
+ easy to expand

- low thermal capacity
- operating characteristics (low charge/discharge capacity, heat pump recommended)
- limited choice of location
- no thermal insulation possible on sides and bottom
- maintenance/repair difficult or not possible



Aquifer Thermal Energy Storage (ATES)

+ very low construction costs

(+) medium thermal capacity

- low thermal capacity

(-) operating characteristics (low charge/discharge capacity, heat pump recommended)

- site selection very limited
- no thermal insulation possible, relatively high thermal losses

Status of district heating systems

In Denmark, the integration of large thermal energy storage is an essential component in the heat supply of district heating (DH) networks. In Austria, the current situation is that only small TES are integrated into DH networks. In Austria, 14 % of the total heat demand (22.4 TWh/a), equal to 7.4 % of the total Austrian energy demand for electricity, industry and transportation, is provided by district heating [4].

The final energy demand for space heating and domestic hot water in Austria is expected to decline from currently about 100 to 78 TWh/a in 2025 considering a current policy scenario. Taking only supply areas with heat densities larger than 10 GWh/km^2 (based on 90 % connection rate) as suitable for DH, a potential for additional district heating supply of 63 TWh/a was estimated [5]. The majority of the operational DH networks consist of 2.000

small and medium sized DH networks, representing about 70 % of the total DH production. The remaining 30 % are large-scale urban DH networks in Vienna and the larger Austrian cities like Graz and Linz. The main energy sources are natural gas, municipal waste, biomass and industrial waste heat. These networks are usually operated at temperatures from 80-130°C, representing 2^{nd} and 3^{rd} generation DH networks. The upcoming energy strategy for 2030 supports wide-scale implementation of DH. Hence, utility companies expect annual growth rates of approximately 2 % [5] in terms of supplied heat, leading to an increase of about 5 TWh within ten years.

Current challenges are the lowering of supply temperatures and the integration of renewables and industrial waste heat. Large thermal energy storage may here increase the viability of DH networks by supplying seasonal storage capacity for abundant heat from renewables (e.g., solar thermal) or industrial heat in summer and consequently are vital for the decarbonisation of our heating supply. Furthermore, storage may lead to additional buffer capacity in case of load and demand fluctuations. A multi-purpose strategy of large thermal energy storage in combination with other technologies such as heat pumps or renewables and utilization of flexible energy generation potential is therefore of high interest for energy and district heating supply companies.

Current large thermal energy storages in Austria are tank storages, mainly used for load/demand balancing and short-term storage of excess heat. No practical experience with seasonal or sub-surface storage technologies nor with the integration of even larger storage units in DH networks is currently available in Austria.

2.2 Where and how to apply LTES

Large thermal energy storage concepts offer the opportunity to bridge the temporal gap between thermal demand and supply. From the four basic technologies for large-scale thermal energy storages described in 2.1, both PTES and TTES in principle combine large storage capacity with high charging and discharging powers: large volumes can store large energy quantities and can act both as a short-term and as seasonal storage with high charging and discharging capacities up to several 100 MW. Moreover, they can store higher temperatures thus basically providing higher storage densities.

PTES and TTES technologies are used as starting point for the gigaTES large thermal energy storage, or **LTES**. The definition within this publication for LTES is, that they are water storages with volumes of more than 50,000 m3, that are built mainly below ground level and that can store heat with temperatures up to 95 °C. Consequently, LTES are suitable for storing excess heat from different sources with a constant supply profile such as geothermal and waste incineration or with changing and even volatile profiles such as solar thermal or industrial waste heat (see Figure 1). Furthermore, integration of Power-to-Heat applications such as heat pumps are possible with LTES offering an excellent cost to thermal storage capacity ratio in comparison to the other TES options.

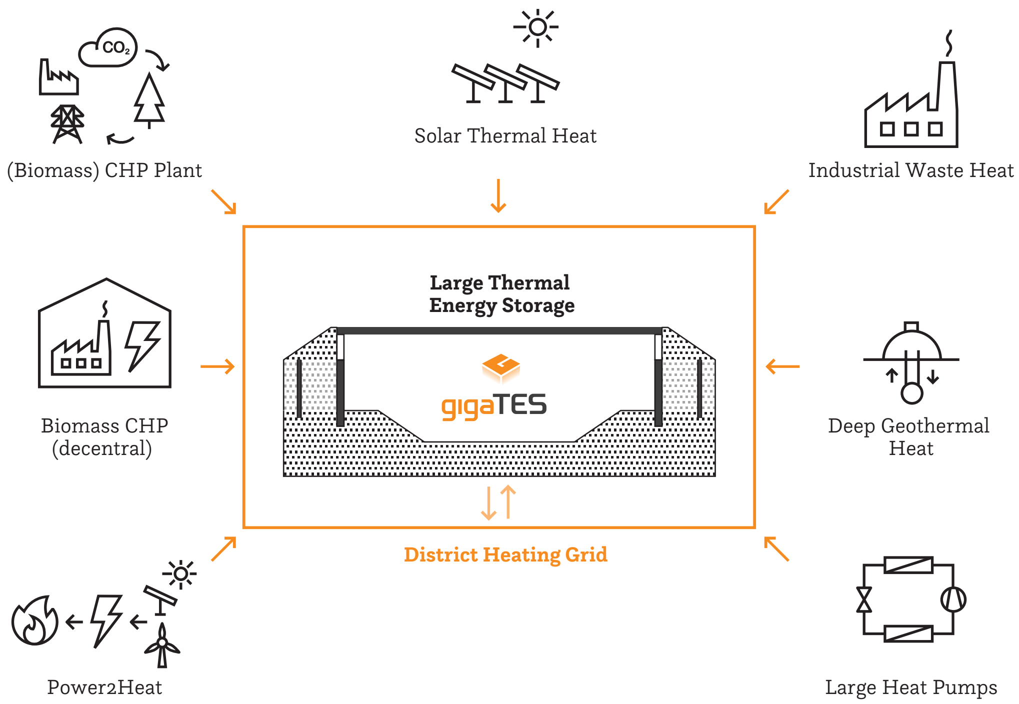


Figure 1: Large thermal energy storage as a pivotal technology in district heating systems, enabling the further uptake of fluctuating renewable sources and providing flexibility to the district heating grid and to the electricity grid through power to heat.

A potential application of an LTES in a more seasonal manner and its implications on the heat supply can be found in Figure 2. Assuming a supply portfolio consisting of base load providers such as geothermal, waste incineration and a resulting excess heat in summer as well as solar thermal, this excess heat and solar thermal can be stored and used in times of high demand, in periods where existing peak load capacities are exceeded and when economically beneficial.

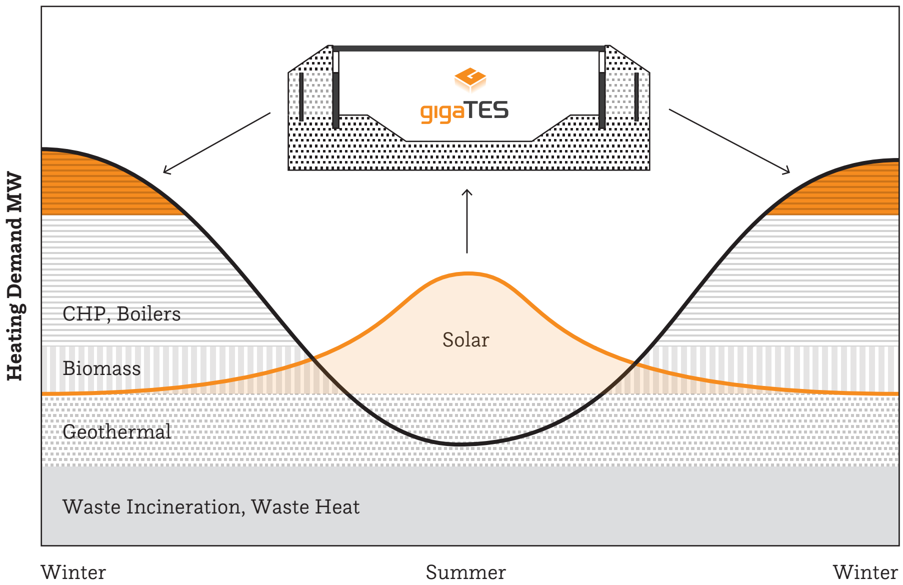


Figure 2: Example for LTES integration in a DH system with a diverse supply portfolio

LTES concepts such as developed in gigaTES show specific costs higher than those for Danish PTES installations (see Figure 3). This is understandable, as Austrian boundary conditions are more challenging (e.g. system temperature levels, (hydro-)geological conditions). GigaTES LTES are only at the beginning of the technology development path, with still a number of development challenges to be mastered.

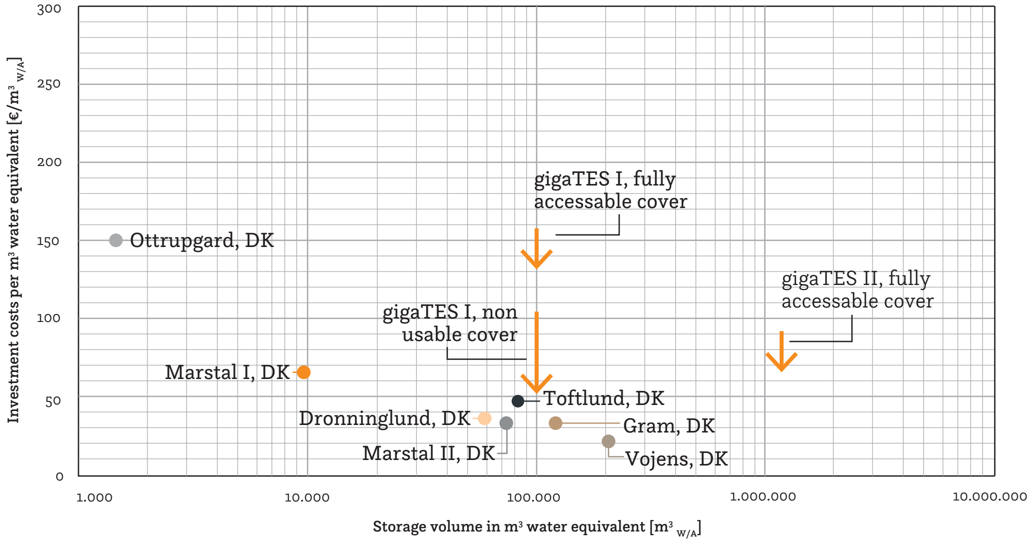


Figure 3: Specific storage investment costs of PTES demonstration plants in Denmark (without VAT) [6]. Costs are very dependent on specific regional boundary conditions. The specific costs for LTES developed in the gigaTES project are added to the figure. These costs are even more dependent on the local conditions and on the chosen construction technology, the desired quality (lifetime) and the application of the storage. The costs are based on first evaluations for pilot projects and will be lowered when they are ready for the market (indicated by the arrow downwards).

2.3 Boundary conditions for LTES application

When and how to apply LTES and to realize them depends on a large number of boundary conditions including technical aspects such as characteristics of the connected DH system (e.g. system temperatures) or (hydro-)geological properties (e.g. presence of groundwater, space availability and cost of land) as well as on organisational and administrative aspects such as local planning regulations. More than one hundred boundary conditions (see Figure 4) and influencing factors (see Figure 5) for a LTES have been identified and categorized within gigaTES, see Appendix D. Boundary conditions in this context are the conditions specified by the actual local setting, which cannot be influenced during project planning and therefore must be used as given quantities. Next to boundary conditions, influencing factors here are defined as those conditions that are generated by a certain choice in the design process. They need to be taken into account in the design steps, but can be changed actively through choices in the design process. Both boundary conditions and influencing factors may affect the storage key performance indicators.

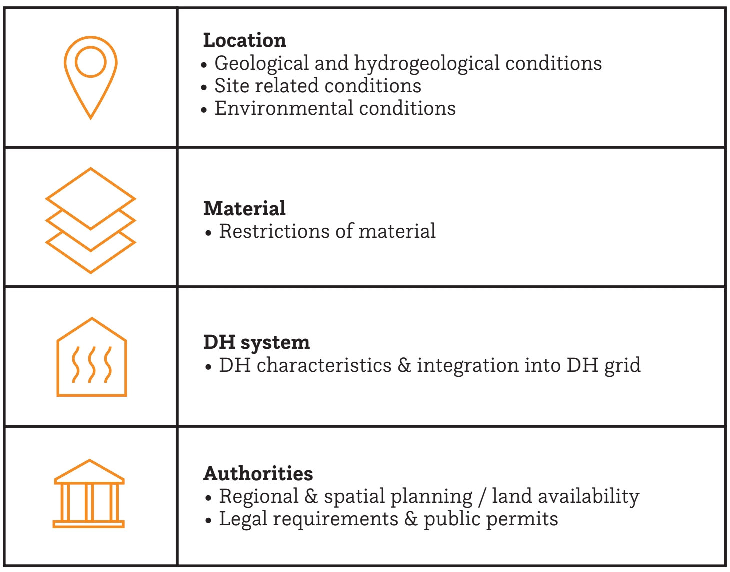


Figure 4: Categories for boundary conditions

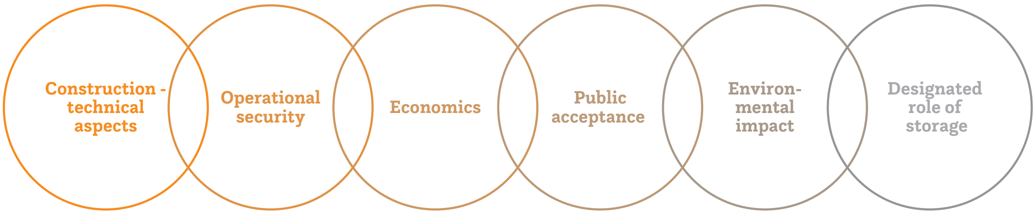


Figure 5: Categories for influencing factors

During the different phases of the project different boundary conditions and influencing factors are relevant, Figure 6 gives an overview on the boundary conditions and influencing factors during the project development:

At the beginning, in the concept phase, the most relevant boundary conditions are the district heating system characteristics such as the network temperatures, the load curve (i.e. the energy production and the peak load). All these characteristics have an influence on the designated role of the storage. With these boundary conditions and influencing factors, the site selection for the storage takes place. At this phase, relevant boundary conditions are location-based aspects as well as boundary conditions concerning the DH system. From the beginning of the project, it is also important to pay attention to the boundary conditions concerning authorities. The role of the storage and the location-based aspects together with aspects concerning public acceptance and environmental impact have an influence on the design of the storage, thus on the construction technical aspects and the materials used. The design of the storage has a major impact on the investment cost, thus on the economics. To be aware of possible risks during the project and to detect cost drivers, the analysis of the boundary conditions and influencing factors at the beginning of the project is relevant.

	Site selection	Design & Construction	Commissioning & Operation
Influencing factors	**Designated role of storage** • Temperature profiles • Load profiles • Charging / discharging • Heat sources	**Design & construction criteria** • Civil engineering considerations • Material properties • Public acceptance	**Operational security and Economics** • Operation • Security & maintenance
Boundary conditions	**Integration in DH grid** • DH system characteristics • Temperature profiles • Network dimensions • Extension plans • (Hydro-)geological conditions	**Sites specifics** • (Hydro-)geological conditions • Environmental conditions • Regional & spatial planning • Legal requirements	

Figure 6: Overview boundary conditions and influencing factors during the phases of the project

Examples of how these boundary conditions influence the feasibility of a LTES are:

- The hydrogeological conditions at the site directly influence the investment costs as they influence the construction measures and thus costs, but also have an indirect impact on the geometry of the LTES and necessary requirements, for instance for thermal insulation (maximum available surface area, maximum achievable depth, etc.).

- The connected district heating system determines the operating mode and charging / discharging of the LTES and thus the type of storage system (short- or long-term storage). The system temperatures do not directly influence the maximum storage temperature, but may determine the potential need for post-heating after discharging from the LTES as well as the choice of materials, such as liner and thermal insulation.
- The availability and affordability of a suitable location in the vicinity of a DH line with a sufficient capacity is vital.

3 Design for LTES

Based on storage constructions already realized in Sweden, Germany and Denmark [6], constructions were developed that can contain significantly larger volumes to function as long-term storage. The closer a storage is located to the city, the higher the costs for the required land and the more important is the requirement to be able to use the surface during the operation of the storage.

Design challenges result from these requirements. In order to leave the smallest possible footprint, a deep construction method is needed and consequently, constructive steps have to be taken to shield the groundwater from overheating as well as to protect the TES from excessive thermal losses. Different design options have been developed for different volume ranges, land availability and geotechnical ground models.

Constructions were also developed for the storage walls and covers that can meet the specific requirements of a LTES. With the design options that have been developed, solutions can be found for various framework conditions at different locations. When the location is known, these basic solutions must be adapted for the specific site.
In the following, the applied special geotechnical engineering methods are presented, in order to show the building methods that are needed for the realization of LTES structures. After that, the possible storage constructions, with their wall compositions and groundwater handling concepts are illustrated. In the final two sections, the different cover concepts and the wall construction concepts are described in more detail, including the mock-ups.

3.1 Special civil engineering components for LTES

Large excavation pits need a correspondingly large space, which is why they usually cannot be realised in a densely built, urban environment. Vertical wall construction methods are needed to minimise the amount of space required. Two most important construction methods are shortly introduced here.

3.1.1 Diaphragm wall (slurry trench wall)

A rectangular slit is created in the ground by excavating the soil, using the gripper or milling method, while filling in a support suspension made of mainly Bentonite and water. In further steps, the reinforcement cage and a joint-board to the adjacent wall-element are installed inside the open slit, then concrete is filled using the contractor method. By lining up individual elements and installing special joint tapes in between, a structurally tight wall is created. (see Figure 7 and Figure 8)

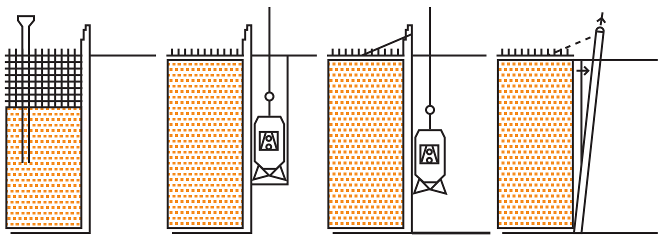


Figure 7: Manufacturing phases of a diaphragm wall [7]

Figure 8: Finished elliptical diaphragm wall shaft - top view [©PORR]

3.1.2 Overlapping insulating bore pile wall

For construction pit securing, large bored piles can be used as intermittent, contiguous or secant pile walls. Large, bored piles are usually manufactured fully cased (see Figure 9), using the gripper or rotary drilling method. After excavation of the borehole, the reinforcement cage is installed and concrete is filled in, using the contractor method. If the ground conditions allow, also so-called continuous flight auger piles can be manufactured. In this method, concrete is poured directly via a core tube while the endless screw is being pulled, after which the reinforcement is pushed into the fresh concrete column.

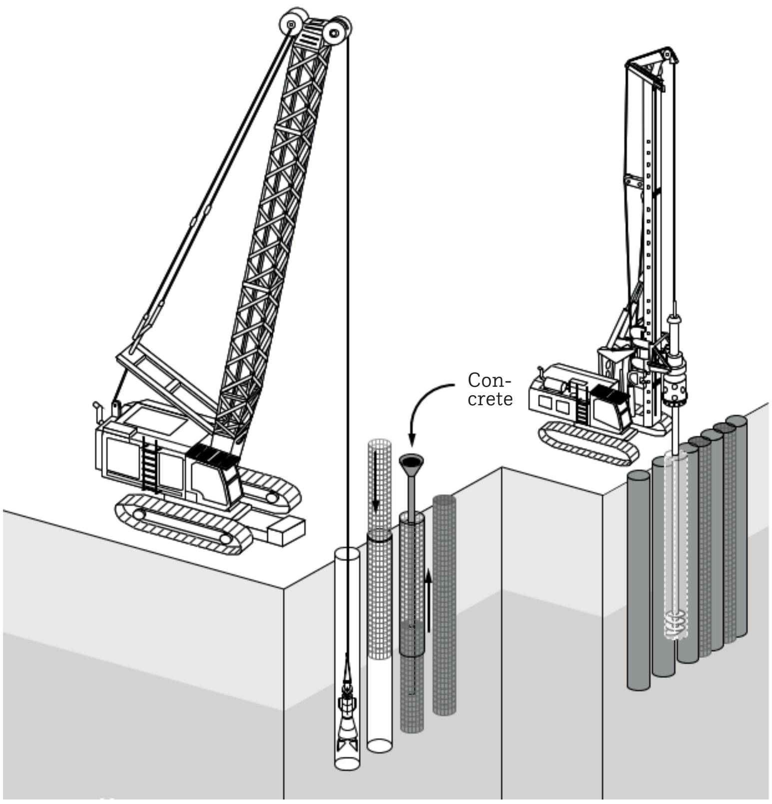


Figure 9: Manufacturing methods of an insulating bore pile wall. Left: fully cased grab-excavation. Right: continuous flight auger piles [7]

3.2 LTES construction types

Now, a short overview is given of the existing and new construction types for a LTES. First described is the shallow pit construction, as is practice now in Denmark. Then four novel construction types suited for building below groundwater level are defined: a hybrid pit / pit with embankment (or deep pit), a hybrid tank, a diaphragm wall tank and a tank.

3.2.1 Shallow pit

Currently, this construction (see Figure 10) is mainly carried out in Denmark. The excavation depth of the storage basin is selected so that the excavation bottom is above the groundwater level and the excavated material can be used as embankment fill on site. This construction method is very easy and cost efficient. However, adapting this construction method for larger volumes is limited because of the very large land required, as can be seen in the figure below (volume 1.0 million m^3 - dimensions 300 x 300 m). Since the cost of a thermal insulating floating cover (see chapter 3.3) can be very high, the large surface area also increases the total cost of the construction. Moreover, the large surface area to volume ratio leads to increased thermal losses.

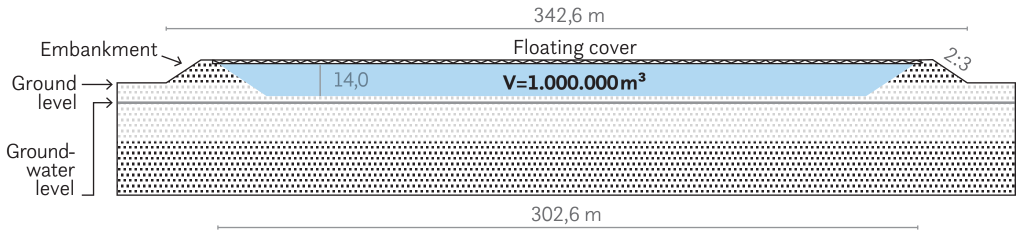


Figure 10: Schematic of a shallow pit, example of 1,0 Mio m^3 [step©]

3.2.2 Hybrid pit / pit with embankment - deep pit

The cost of a floating cover that is thermally insulated and fully accessible is very high. To reduce the floating cover area, the excavation depth must be increased. A first step is the excavation of an embanked pit. If groundwater is present, a surrounding sealing wall or cut-off wall can be constructed. Within this sealing ring, the groundwater is kept low with vertical filter wells. In order to enable a proper attachment of the storage cover construction to the side walls, the above ground section of the storage walls must be built vertically. A possible construction for this can be a cantilever retaining wall. This is backfilled with the excavated material and thus increases the above-ground volume of the reservoir, as can be seen in Figure 11.

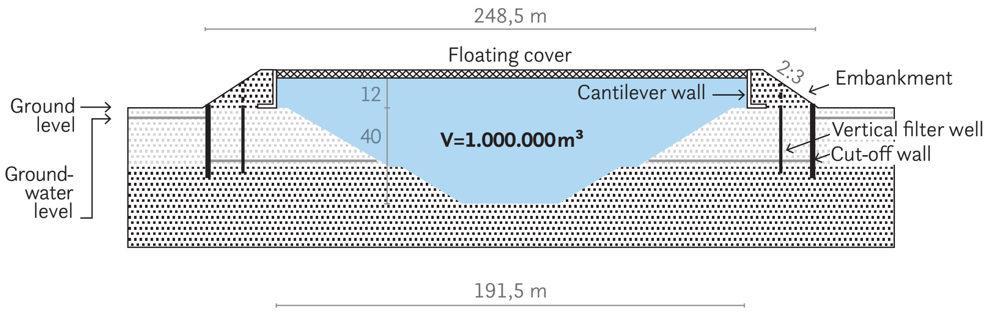


Figure 11: Schematic of a hybrid pit / deep pit with cut off wall, example of 1,0 Mio m^3 [step©]

3.2.3 Hybrid tank - anchored diaphragm wall (square layout) with base embankments

The design (see Figure 12) of vertical storage walls can further reduce the size of the surface. The vertical storage walls are constructed using the diaphragm wall method described above. To block off the groundwater, the diaphragm walls must be routed all the way into the aquiclude. In the course of excavation, the diaphragm walls are tied back with ground anchors so that they can absorb the earth pressure for the construction stage until the reservoir is filled. The surrounding cut-off wall must be sufficiently distant from the diaphragm wall not to be penetrated by the anchors. In the lower area, the pit can be further deepened by an embanked excavation.

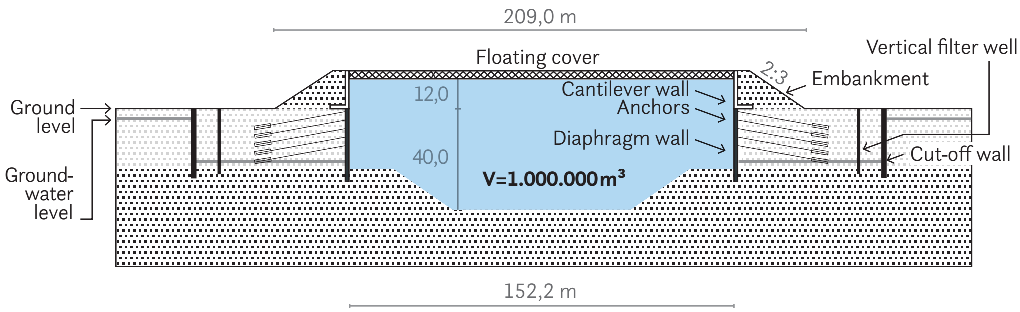


Figure 12: Schematic of a hybrid tank, example of 1,0 Mio m³ [step©]

3.2.4 Diaphragm wall tank - anchored diaphragm wall (square layout)

The optimal ratio between excavation volume and surface can be achieved if the storage walls are vertical down to the excavation level. However, the production accuracy of diaphragm walls limits the depth to approximately 50 m. This design (see Figure 13) also has high technical requirements due to the anchoring work and the additional cut-off wall to be constructed if there is groundwater.

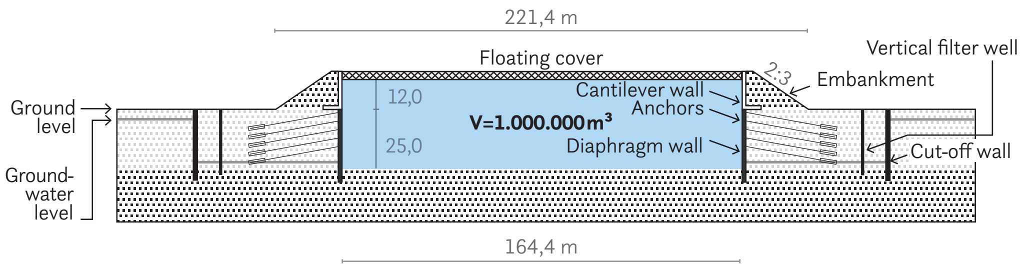


Figure 13: Schematic of a diaphragm wall tank, example of 1,0 Mio m³ (step©)

3.2.5 Tank (cylindric diaphragm wall shaft)

Due to the load-bearing effect as a pressure ring, a diaphragm wall shaft that has a circular (or elliptic) floor plan can be built without additional stiffening elements. The circular layout plan is approximated by a polygonal configuration of diaphragm wall elements. This design has already been built up to a shaft diameter of 50 m, as shown in Figure 14 as an example. The diameter for such shafts is limited to 65 m as with larger diameters, the pressure ring would become impractically large and expensive. With a maximum depth of about 50 m, the volume then is limited to approximately 200,000 m³. For the cover of the storage tank, both a floating cover and a self-supporting cover are possible. Cantilevered roof structures with a span of 65 m are state of the art and can also be designed to allow a low payload.

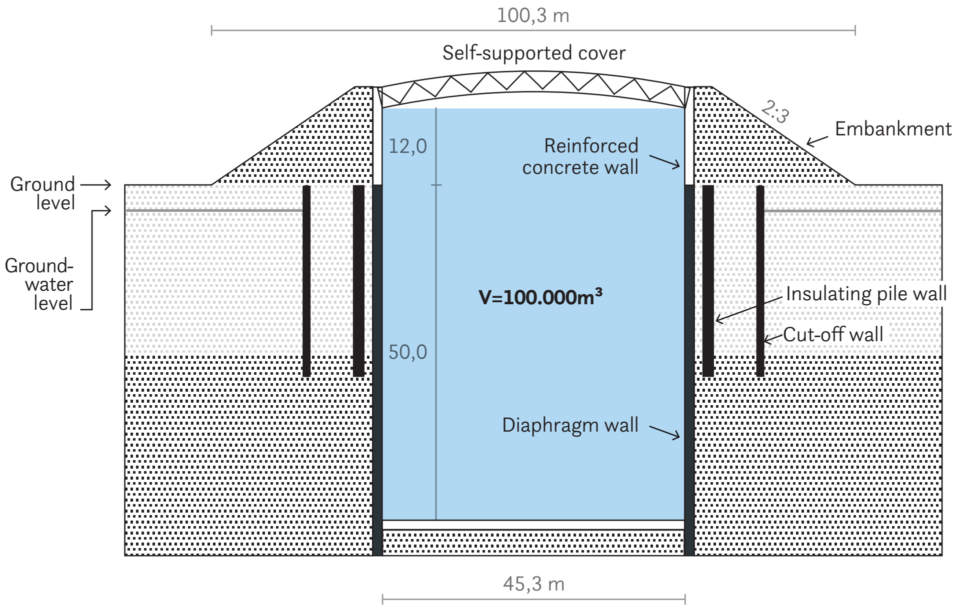


Figure 14: Schematic figure - tank with volume of 0,1 Mio m³ and self-supporting cover (step©)

3.2.6 Construction types overview

The following table gives an overview of general and construction features of the 5 different construction types described above.

Table 2: Overview of general and construction features of the 5 different construction types

Construction types overview		**Shallow pit**	**Hybrid pit**	**Hybrid tank**	**Diaphragm wall tank**	**Tank**
		excavation above ground-water	pit with embankment - deep pit	anchored diaphragm wall with base embankments	anchored diaphragm wall	cylindric diaphragm wall shaft
General information	**required land use** (depending on ...)	**very large** (excavation depth, depth of ground water)	**large** (excavation depth, volume, embankment angle)	**medium** (excavation depth, volume, geology, depth of aquiclude)	**low** (excavation depth, volume, geology, depth of aquiclude)	**very low** (the storage depth)
	construction costs	low costs for excavation, immoderate costs for cover due to the large area	low costs for excavation, high costs for cover due to the large area	high costs due to the special civil engineering works and especially because of the anchor	high costs due to the special civil engineering works and especially because of the anchor	high costs due to the special civil engineering works in relation to small reachable volume
	max. storage volume	**no limit**	**no limit**	**no limit**	**no limit**	**limited to 200.000m³**, for larger volumes a multiple number of tanks is required
	storage depth restrictions	level of ground water	no limit	max. depth of diaphragm wall 50 m	max. depth of diaphragm wall 50 m	max. depth of diaphragm wall 50 m
Construction features		embanked open excavation, In order to use excavated material, embankment up to h =15 m	embanked open excavation with earth berm	anchored diaphragm wall with base embanked excavation in the area of the aquiclude	anchored diaphragm wall,	diaphragm wall shaft, load-bearing effect as a pressure ring, maximum diameter is 65m
Cut off wall		**none**	**required** (in case of presence of ground water)	**required** (in case of presence of ground water)	**required** (in case of presence of ground water)	**required** (in case of presence of ground water)
Excavation effort (depending on excavation depth)		**low**	**low**	**medium**	**high**	**high**
Special civil engineering (depending on excavation depth)		**no**	**low**	**medium**	**high**	**high**
Cover effort (depending on cover area)		**very large**	**large**	**medium**	**low**	**low** (optional self-supporting cover)
Insulation		typically, only cover insulated	cover insulated insulating bore pile wall	insulation of embankment possible	cover insulated insulating bore pile wall	cover insulated insulating bore pile wall
Liner work effort		**low** sloped pit wall	**low** sloped pit wall	**medium**	**high** vertical tank wall	**high** vertical tank wall
Deconstruction effort		low only backfilling	low only backfilling	medium demolition and backfilling	medium demolition and backfilling	medium demolition and backfilling

3.3 Cover constructions

The design of the cover surface has a significant impact on the thermal losses. For this reason, the thermal insulation of the surface is an essential requirement for the cover construction. Another important requirement is the usability of the cover. The high space requirement of a LTES can be compensated by the fact that the area is usable during the operating phase by providing load bearing for pedestrians or even for light traffic. Possible solutions to the associated technical challenges, such as high temperature of the storage medium, water level fluctuations, temperature change of the storage medium and dynamic loading, were investigated for three different lid constructions.

3.3.1 Floating cover

The construction of the proposed floating cover (see Figure 15) is modular. The modules are assumed to be 4x4 m in size and welded together on site along a steel collar. These modules are made of stainless steel and have 4 round floats each, that can be larger or smaller according to the selected payload. The choice of steel depends on the temperature of the storage medium and the water quality. The floats are dimensioned in such a way that a gap remains between the water surface and the undersurface of the lid. This gap or cavity serves as a means to equalize the pressure. A patented welded joint is used for the corner connection, which makes it possible to absorb the dynamic movements due to load and temperature changes. For the thermal insulation level, solutions were developed for compression-resistant thermal insulation (i.e., compacted glass foam gravel) and for non-compression-resistant thermal insulation (e.g., rock wool). Both constructions can be designed in such a way that the desired payload can be applied. First solutions to take up the forces due to relative movement of modules have been generated also.

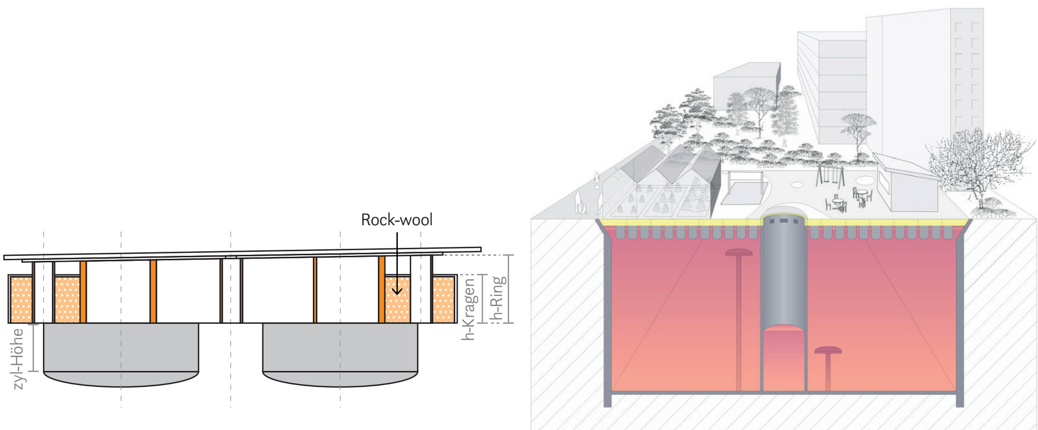


Figure 15: Schematic representation of the floating cover detail / overview with compensation tank

3.3.2 Submerged cover

The submerged cover (SmC) concept is the second cover concept developed in the gigaTES project. Details can be found in [8]. Basically, the SmC tightly separates two water reservoirs, whereby no water exchange can occur between the two reservoirs, thus preventing the SmC from floating up. The lower, hot reservoir is the storage medium, while the upper reservoir remains “cold” due to the thermal insulation of the SmC. This is achieved through a flexible design of connecting structures of the individual cover modules and connection to the storage wall, depending on the water level fluctuations of the storage medium that may occur. The SmC is thus not a static construction but allows height adjustment depending on operational requirements. A challenge in the design are the four corners of the construction, where possible movements in three directions have to be taken up. Figure 16 shows a simply fied illustration of the essential components as well as a perspective view.

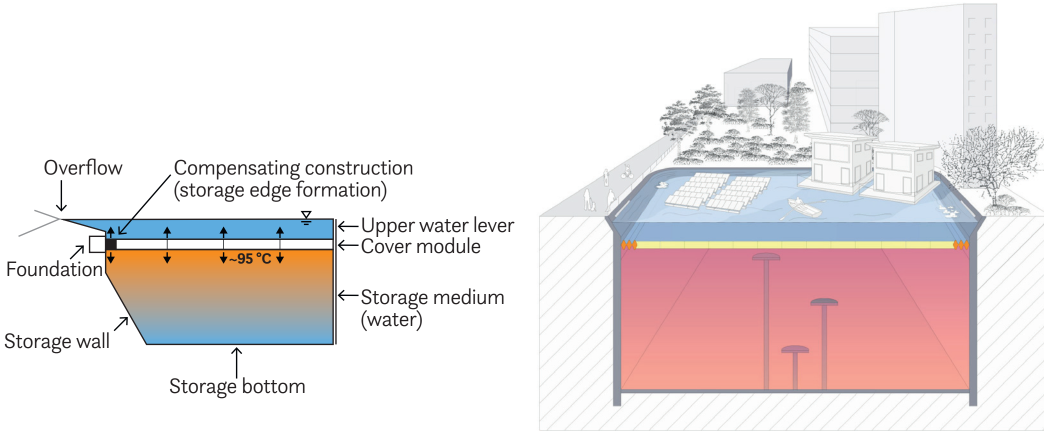


Figure 16: Schematic representation of the SmC concept with main components (left), perspective view (right) [8]

3.3.3 Self-supporting cover

The possibilities for a self-supporting storage tank cover were also investigated [9]. The following constructions for a round storage tank (cylindric diaphragm wall shaft) as well as for square storage tank geometries were investigated:

- Concrete shell (circular) made of UHPC (ultra-high-performance concrete).
- Steel space truss (round), radially arranged steel girder segments
- Steel framework, square ground plan

The calculations were carried out for a span of 65 m and for different live loads. It was shown that economic solutions can be found for a payload of 3.5 kN/m^2. Higher payloads lead to uneconomical, very massive constructions with a large cantilever, that severely restricts usability. Figure 17 gives an impression of a self-supporting steel framework. For application as an LTES cover, the design should include liner and thermal insulation.

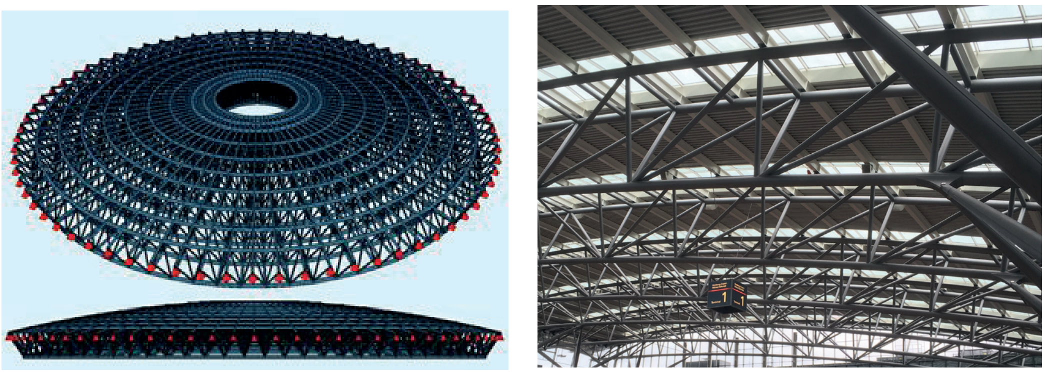


Figure 17: self-supporting steel framework [9] (left), example steel framework –Airport Hamburg (right)

3.3.4 Mock-up of a cover detail

In the context of the studies of the possible design solution of the floating cover, the necessity to know the actual performance of insulation materials in real-operation conditions called for a detailed investigation. In particular, the presence of residual moisture (from rainfall and infiltrations), the heat flux direction and the high temperature difference are crucial parameters to be considered in the material selection.

Considering the favourable properties of low density, high ageing resistance and low nominal thermal conductivity, foam glass gravel (FGG) is a suitable material for this application. However, the porous nature of this material can lead to increased thermal losses. In order to answer the questions concerning the actual FGG performance in presence of moist conditions and unfavourable heat transfer direction, a mock-up of the cover was designed, built and set up in a climate chamber. The mock-up consisted of small-scale cover modules filled with loose FGG (see Figure 18). Four mock-ups were realised to gain a detailed overview of the behaviour of FGG under three different compaction configurations; one mock-up with loose uncompacted FGG was kept as reference. In order to simulate the operation conditions that can be encountered in a TES cover, a heating plate was placed under the lower side of the case to ensure a constant set point temperature of 60°C.

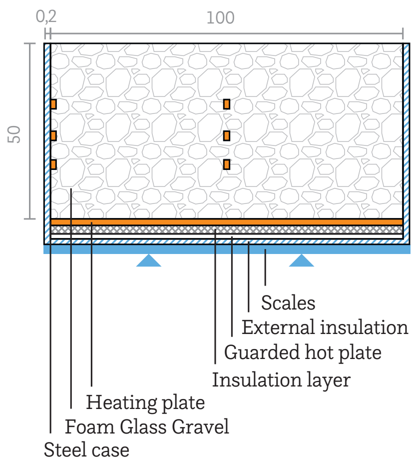


Figure 18: Schematic side view of TES cover mock up (measures in [cm]). (left) Actually, realized mock-up. (right)

Aim of the test was the definition of the time required for the complete evaporation of a predefined amount of water to achieve a condition of dry substrate and the evaluation of the actual insulation performance of the module in presence of a negative vertical temperature gradient. In order to measure the gradual weight loss caused by the water evaporation, the case was placed on a scales. From the results it was possible to see that an increase in the compaction degree (i.e., higher densities) leads to better insulation performance with respect to the uncompacted reference sample, thanks to the lower convective heat transfer within the bulk. On the other hand, the lower convection reduces the mass transport and the evaporation thus slowing down the drying process. The use of convection brakes is an interesting solution to limit the convective heat transfer. However, the moisture transport must be guaranteed to ensure a complete drying of the material, therefore these barriers must be able to simultaneously ensure moisture transport and minimize the air circulation that drives the convection and increases the specific thermal losses.

3.4 Wall constructions

Different constructions were developed for the storage wall in the gigaTES project. In principle, a distinction is made between uninsulated and insulated wall and bottom.
In the case of an uninsulated storage wall, a liner must be installed to ensure that the storage medium cannot leak. The lining material depends on the temperature profile of the storage tank and is chosen to have a lifetime of at least 50 years.

- HT-high temperature 90° - 60°C stainless steel-based liner
- LT-low temperature 80° - 30°C polymer-based liner.

For the insulated wall, both constructions with internal thermal insulation and external thermal insulation have been developed.

3.4.1 Internal thermal insulation

In the context of the project, numerous variants for internal thermal insulation were discussed and the advantages and disadvantages of the constructions were evaluated. A particular challenge resulted with the civil engineering variant with vertical diaphragm walls due to their very irregular surface after uncovering (excavation). These irregularities can be levelled out with a bulk thermal insulation. To contain the storage medium, a vapour-tight sealing layer is necessary, consisting of a stainless-steel liner or polymer liner depending on the temperature profile. For the installation of the liner, a flat surface is needed, which can be formed by a concrete inner shell. Such a wall construction can be made on site or built with prefabricated elements. Different fabrication methods were evaluated, such as using climbing frames or floating assembly islands. The associated cost estimates were used as the basis for the Construction Cost Calculation tool, see section 5.1.

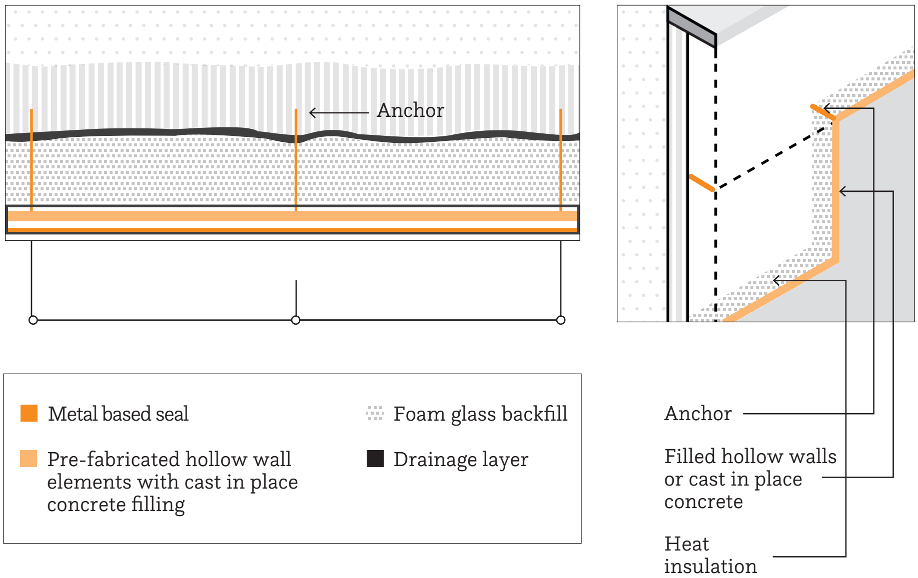


Figure 19: Concept internal thermal insulation wall (© step)

3.4.2 External thermal insulation – insulating bore pile wall

The development of an external thermal insulation is based on the technique of an overlapping bore pile wall, see 3.1. Instead of filling the bored piles with concrete, the piles are filled with foam glass gravel. The result is a soil replacement with heat-insulating material. A patent application has been submitted for this production method [10].

In two large-scale tests, the production, installation, and thermal behavior of such an insulating bore pile wall were analyzed. At the same time, mock-up tests were carried out, combined with simulations on the thermal insulation behavior of the installed foam glass gravel. The insulation tests (described in the subsection 3.4.3) are not focused on the Foam Glass Gravel, but on its application as insulation material for the insulating pile wall.

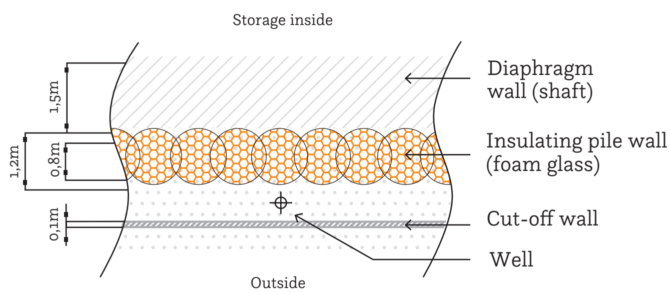


Figure 20: Left: concept drawing of the insulating bore pile wall – horizontal section [10]; Right: mock-up of bore pile filled with foam glass gravel

gigaTES
Design for LTES

3.4.3 Mock-up insulating bore pile wall

A patent for the newly developed solution of insulating bore pile wall was registered. Maybe this sentence can be deleted since it was specified in the previous paragraph. Together with the concept development, field tests supported by numerical simulations were carried out.

A downscaled pre-mock-up of an insulating pile was built and used to test the thermal behaviour of different insulation material configurations (i.e., uncompacted, compacted, and with different granulometries). Field tests were then conducted on a construction site in Vienna. Figure 21(left) shows the construction site where the tests were carried out and the drilling machine used to build the piles. In this field test phase, the insulation performance of the drilled piles filled with compacted foam glass gravel was studied with thermal response tests supported by numerical simulations. Figure 21(right) shows the axisymmetric temperature contour plot of the upper 2 meters of one of the investigated insulating piles surrounded by the ground; a measuring probe was located vertically along the axis of the pile (at radius 0 m in the figure) to generate a heat wave (max. 90 °C) that propagated to the surrounding ground and to measure the temperature along the height of the pile during the entire test.

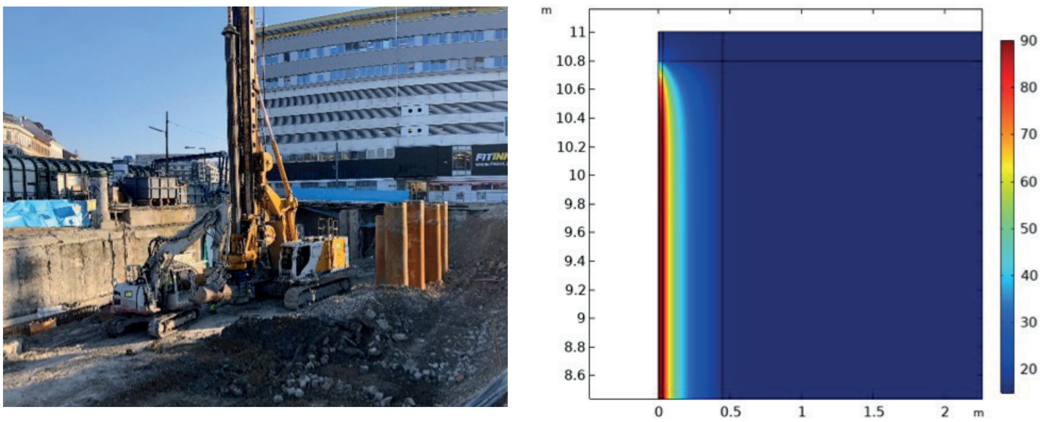


Figure 21: Drilling machine used for the insulating piles [© PORR]. (left)
Temperature contour plot of the axisymmetric model of one of the tested bore piles during the test. (right)

The results of the tests showed that the porous nature of the material and the insulation design (i.e., 3D heat flux distribution) caused a non-negligible share of convective heat transfer due to the bulk porosity and therefore a bad insulation performance of the pile with poorly compacted material. Compacted foam glass gravel, instead, showed a better insulation performance thanks to the reduction of the porosity. The field test confirmed the higher insulation performance of the piles with higher degree of compaction, but at the cost of using larger amount of insulation material.

4 System analysis and case studies

In order to make proper investment choices for a large thermal energy storage, a method to determine the techno-economic performance of the LTES on system level, in a DH network, needs to be in place. The method for making this system level evaluation and techno-economic analysis is explained. Two typical, representative case studies are introduced to demonstrate how the integration of a LTES can benefit the overall performance of the system by greatly increasing the share of renewable energy sources in the networks. One case study is a smaller DH system in terms of heat consumption where a 100,000 m^3 LTES is to be integrated, and the other is a medium scale DH system with a 1,200,000 m^3 storage volume. The primary goal of the LTES is to greatly reduce the running times of fossil based peak load boilers and finally rendering them obsolete during the winter periods by shifting excess solar thermal and geothermal heat from the summer. Two variants are defined for each DH system to showcase both high temperature (supply/return 90 °C/60 °C) as well as representative low temperature systems (60 °C/30 °C) and the benefits such systems will have from LTES integration. This chapter outlines both case studies, their relevant boundary conditions and integration aspects. Chapter 5 then gives a more detailed overview of the LTES performance and the impact on each system.

4.1 Approaches for system level evaluation and techno-economic analysis

In order to fully exploit the potential of LTES technologies, a proper integration of the storages and a comprehensive planning and tuning of the overall energy system is required. This can be guaranteed by taking into account all relevant system components in multi-annual dynamic system simulations. The system is comprised of a heat demanding city and a number of different heat sources, all connected to the LTES. In Figure 22 a schematic presentation of this system is given. The heat balance of the system is calculated over a number of years, until there is no average additional heating of the soil around the thermal storage anymore. System level simulations can also help investigate the impact of varying storage capacities and control strategies (i.e. seasonal storage only or multifunctional with CHP optimisation), as well as the interaction between the storage and other components such as heat pumps and post-heating plants (necessary when network temperatures exceed the maximum temperature of the storage).

The annual production of CO_2 and the electricity demand for heat pumps, if present, is tracked and can be used as optimisation targets. The composition of the different sources and the size and geometry of the LTES can now be changed to test which composition has the best techno-economic and/or environmental results. Besides, the merit order can be changed; this is the order in which, when heat demand increases, the different sources are switched on. For instance, one can choose to first switch on the source with the lowest cost and then the source with the second but lowest cost.

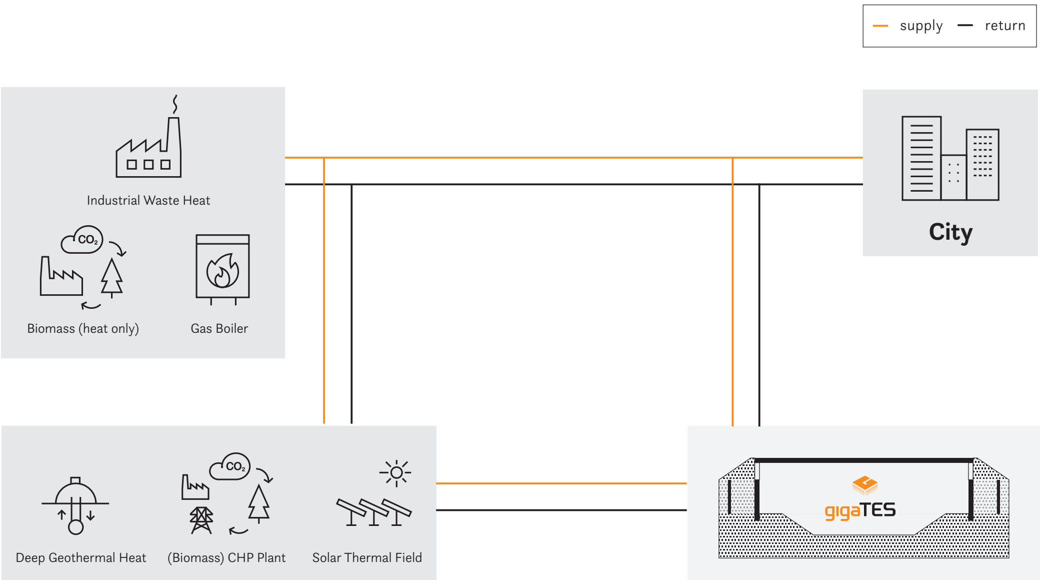


Figure 22: LTES integration concepts

Within the gigaTES project, a number of system level simulations were carried out for defined DH systems and locations to assess the impact of LTES on the overall system performance. Figure 23 gives an overview of which relevant inputs necessary for such analyses were integrated in this evaluation.

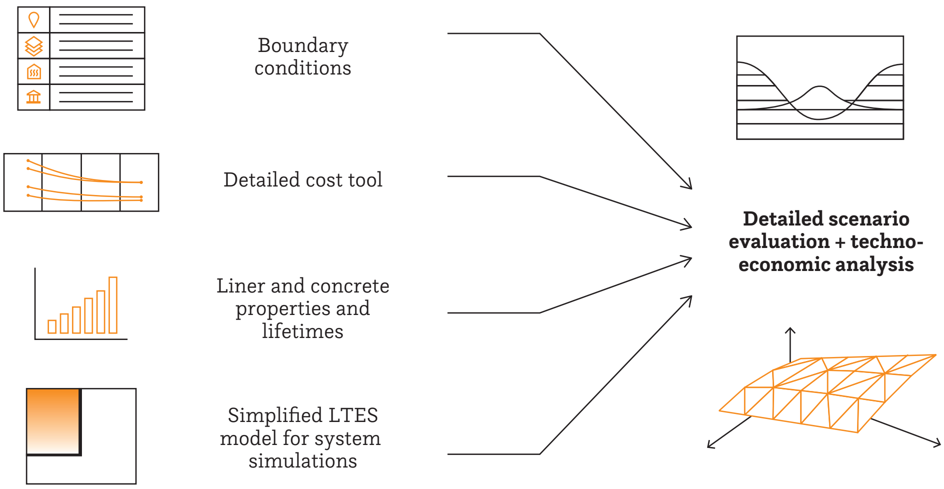


Figure 23: General Workflow for system level evaluations in GigaTES

For the system simulations, one approach is to model all relevant system components in, for instance, TRNSYS, Matlab/Simulink or Dymola, a multi-domain, dynamic simulation environment. Dymola contains many libraries with validated models of system components such as pipes, heat exchangers, hot water tanks, pumps, heat pumps, solar thermal and other heating plants. A suitable model for the LTES model itself was developed during the project. As the model is to be used in a larger system, it should couple good accuracy with fast calculation times. Two main parts of the model are the storage itself, the fluid domain, and the surrounding underground with ground water flow (see Figure 24). The structure and a brief description of the model can be taken from [11]. The model was also validated with real measurement data of the PTES in Dronninglund (Denmark) within the scope of the project [11].

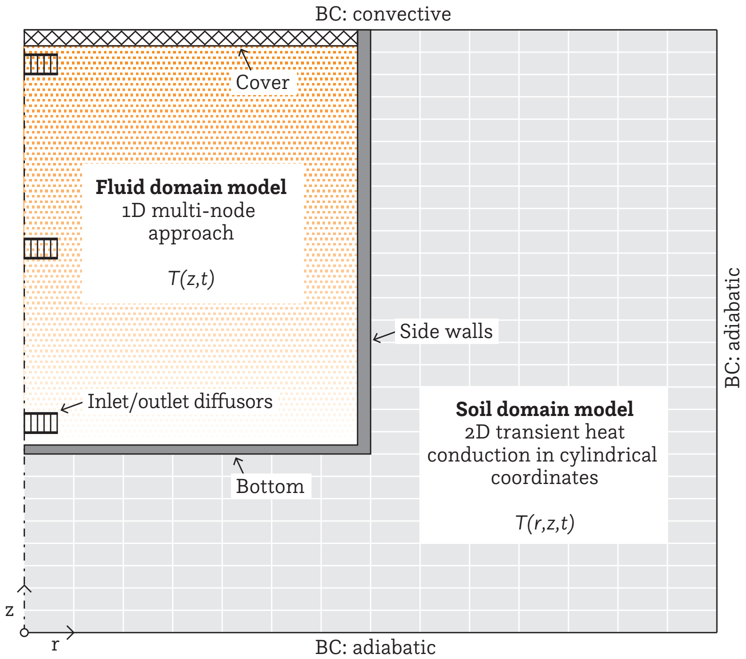


Figure 24: Schematic of the developed simplified LTES model in Dymola [11].

In order to further assess the accuracy, the developed model was part of a comprehensive model comparison together with other LTES models of different simulation tools (e.g. COMSOL Multiphysics, TRNSYS and MATLAB/Simulink[2]). The results of the cross-comparison showed a good agreement in terms of charged and discharged energies, storage temperatures and thermal losses between the developed model and the other models. [12]
The novel Dymola/Modelica LTES model not only closes the gap between detailed component simulations and system simulations, but also enables integrated flexible system modeling due to the Modelica modeling approach and the ongoing extension of the model, for instance with other geometries.

Accordingly, the model was used within gigaTES for system simulations, techno-economic analyses and parameter studies of several case studies of different locations and scenarios. The storage control strategies for these scenarios were either devised using control blocks in Dymola or by pre-defined storage loading/unloading profiles originating from the boundary conditions of the investigated scenarios.

Another approach used within the project was to derive and evaluate load profiles for the LTES based on system models in EnergyPRO. Its built-in MILP solver is used to determine the cost-optimal heat merit order at hourly intervals over a given year assuming a given selection of heat sources, heat demand, and prices for operation, fuels and CO_2 emissions. Since it is not possible to model storage temperatures and thermal losses within EnergyPro, these variables can be subsequently evaluated with a high-detail storage model (e.g. using COMSOL). The corresponding thermal losses are then fed back into the system level model in EnergyPro to assess the overall system performance.

[2] https://www.mathworks.com/products/simulink.html

4.2 Case study city A: Medium scale DH System

A generic DH system typical of those found in an Austrian context was devised to demonstrate the techno-economic and environmental impact of a 1,200,000 m³ LTES on both storage and system levels.

The supply portfolio consists of geothermal heat (12 MW), constant industrial waste heat (2 MW), biomass boilers (4.5 MW) and biomass CHP (8 MW) as well as gas boilers (35 MW) for peak supply. Two operation variants are used: a high temperature (HT) variant with 90 °C and 60 °C supply and return temperatures, respectively and a low temperature (LT) variant with 60 °C and 30 °C. For the HT variant, the storage temperature is 90 °C maximum, while for the LT variant it is 80 °C maximum. Table 3 gives an outline of the main system properties for both HT and LT variants. Figure 25 shows the heat supply curve for the HT variant with LTES integration.

Table 3: Main system properties for City A - LT and HT variants

Property	City A (LT)	City A (HT)
Heat consumption	239 GWh	239 GWh
Heat losses	8 %	10 %
Heat production	258.12 GWh	262.9 GWh
Peak load	64.6 MW	64.6 MW
Summer load	8.2 MW	8.2 MW
T_{supply}	60 °C	90 °C
T_{return}	30 °C	60 °C

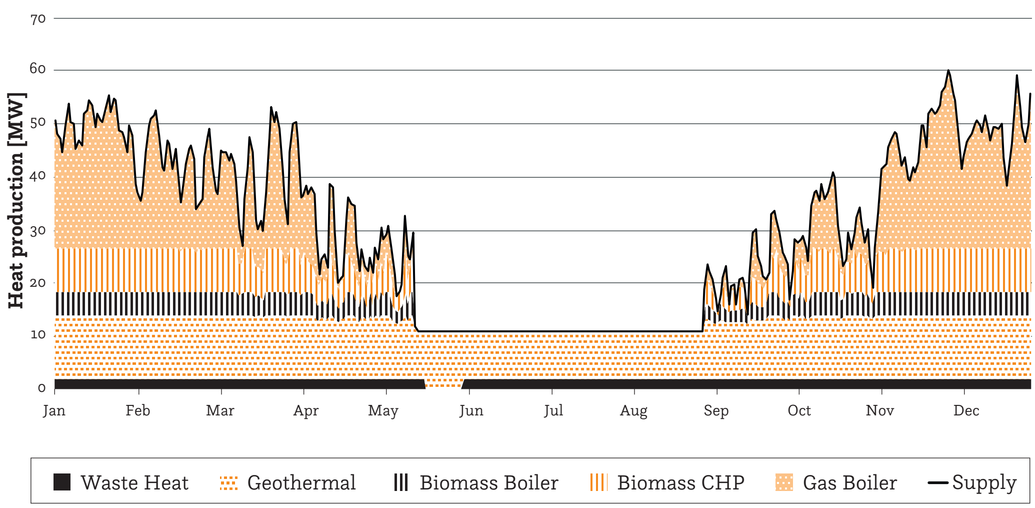


Figure 25: Yearly heat production- city A (HT variant)

Approximately 32 % of the heat demand is to be met by gas boilers which cover peak loads. The base load comprises of heat from geothermal and waste heat with the intermediate loads being covered by biomass and biomass CHP.

Figure 26 gives an outline of the main system concepts for both HT and LT variants. There is a surplus of geothermal heat present in the summer months for the LTES to store. In addition, a solar thermal plant is to be introduced to further utilise the available storage capacity.

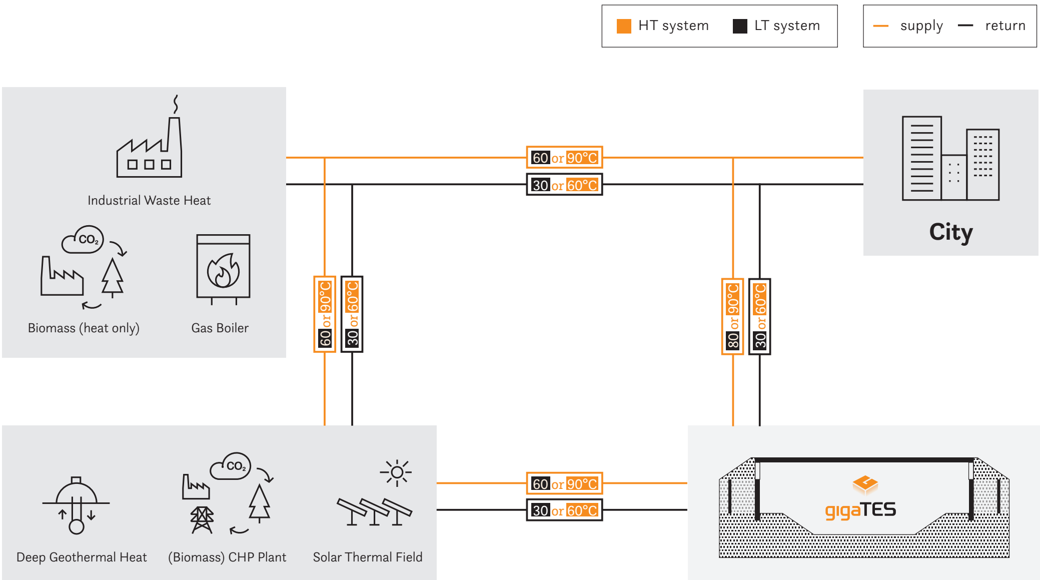


Figure 26: City A LTES integration concepts (HT and LT Variants)

4.3 Case study city B: Small scale DH System

A small-scale DH system of City B was also considered to demonstrate the impact of a 100,000 m³ LTES on the system for both high and low temperature variants with the main grid characteristics outlined in Table 4. The supply portfolio consists of geothermal, (0.4 MW) industrial waste heat (0.2 MW), and biomass CHP (1.2 MW) as well as a gas boiler (2.5 MW) for peak supply.

Property	City B (LT)	City B (HT)
Heat consumption	15 GWh	15 GWh
Heat losses	5 %	10 %
Heat production	15.75 GWh	16.5 GWh
Peak load	4 MW	4 MW
Summer load	0.5 MW	0.5 MW
T_{supply}	60 °C	90 °C
T_{return}	30 °C	60 °C

Table 4: Main system properties for City B - LT and HT variants

The heat production of Case Study B (without inclusion of LTES) was similar to that in City A with scaled down capacities (see Figure 27).

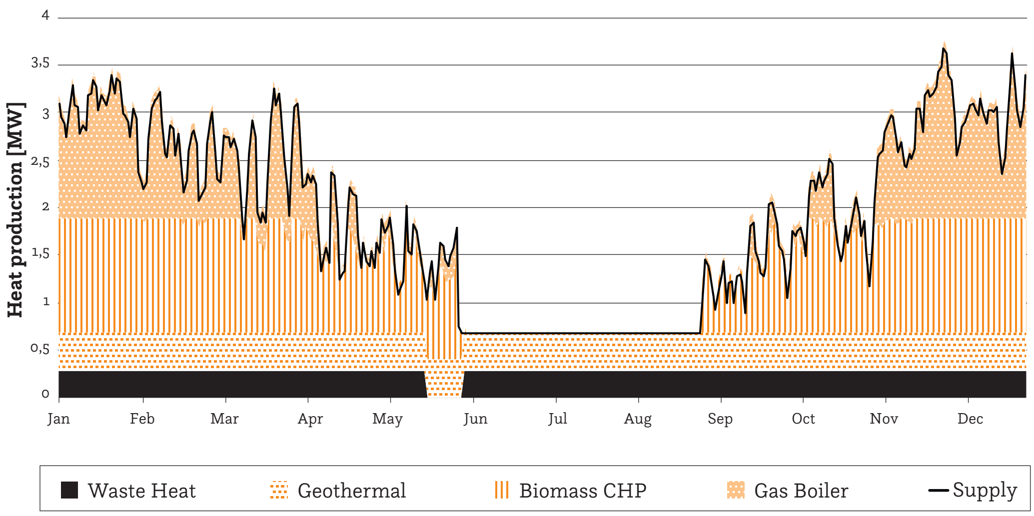


Figure 27: Yearly heat production - city B (HT variant)

Approximately 27 % of the heat demand is to be met by the gas boiler during peak loads with waste heat and geothermal covering the base load. The intermediate load is covered by the biomass CHP plant outside of the summer period. Figure 28 shows the integration concepts for both the HT and LT variants of the system. There is a surplus of solar thermal heat in the summer months for the LTES to store as well as a small amount of charging from the biomass CHP to optimise its operation.

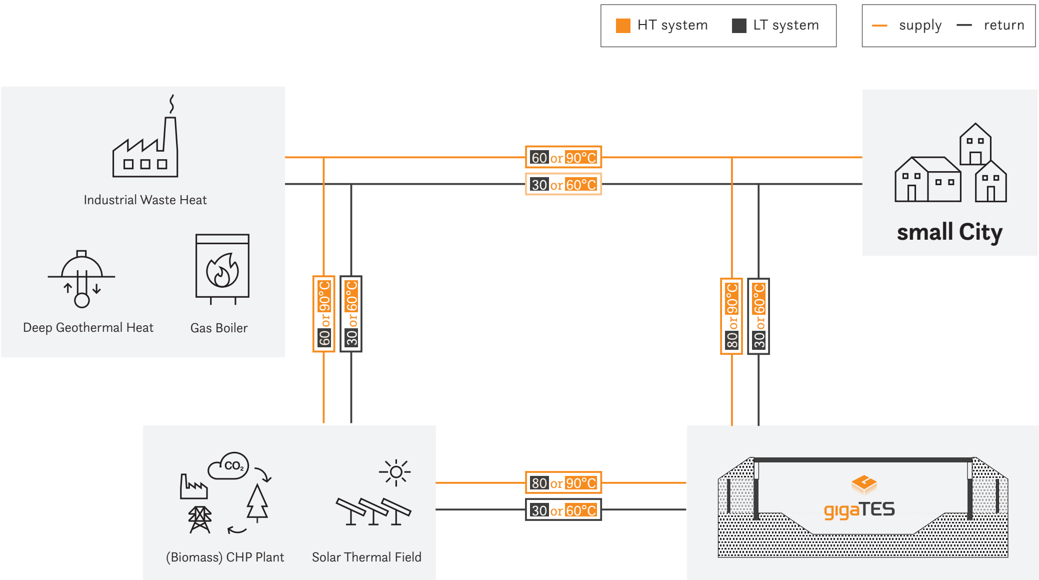


Figure 28:
City B integration concept (LT and HT variants)

The resulting storage energy content plots for each of the above cases (HT and LT variants) can be found in Appendix A.

The selection of a best suited storage design, materials, geometry and their subsequent influence on thermal losses and investment costs are highly dependent on the system boundary conditions. The next chapter will show a more detailed determination of performance and cost of LTES in the two Cities A and B with input from the Construction Cost Calculation Tool developed within the project.

5 Performance and cost of LTES

With the use cases defined in Chapter 4 and the construction concepts from Chapter 3, a choice can be made for the most suited storage concept for a given case. The choice is made on basis of the economy of the concept, in terms of cost per storage unit. The Construction Cost Calculation Tool (CCCT) is used to estimate the construction cost of an LTES. Then, it is demonstrated how the cost tool is used to aid in the selection of the most suitable and cost-effective storage designs for each application and set of boundary conditions. The estimated investment costs and levelized costs of storage (LCOS) are presented for each application scenario as well as the corresponding CO_2 savings and the technical KPI's such as storage efficiency and cycle numbers in order to show under which boundary conditions the developed storage concepts are best suited to and where challenges as well as potential improvements exist, both regarding storage design and DH operating conditions.

5.1 C3T – Construction cost calculation tool

The Construction Cost Calculation Tool (C3T) is an excel-tool based on empirical values. The Excel tool is designed to give an estimate for the expected costs of construction for different design types and sizes of thermal energy storage units. Various details of the construction can be selected, as well as the area of the storage unit to be thermally insulated and which design for the walls and the cover. According to the chosen inputs, the tool gives an estimate for the resulting costs, outlining the different cost-factors, and enables the comparison of the selected design types with regard to their total costs and cost-efficiency.

5.1.1 Input data

In the "input" sheet of the excel-tool, some general assumptions for the design can be given (see Figure 29).

Input parameters

- Specifications regarding the construction ground
- If a cut-off wall is required, the depth can be entered here.
- The temperature profile can be chosen to be either HT 90 °C – 60 °C or LT 80 °C - 30 °C.
- For all building types with embanked excavations, possible slope angles may be entered.
- Concerning the planned construction site, land dedication may be chosen. Different land costs are associated with the respective dedication. In addition, possible construction types regarding the available site are output at this point.
- For all construction types excluding the shallow pit, the desired height of the embankment can be entered here.
- The requirements regarding the load-bearing capacity of the cover construction can be selected as "high" (fully accessible) and "low" (non-usable).
- The thermal insulation for different sections and different materials can be chosen.
- Three different desired storage volumes for the storage units can be specified for a direct comparison

INPUT DATA for all storage construction-types					
version 22.07.2021					
groundwater level:	5.0 m	below ground level			
depth of aquiclude:	15.0 m	below ground level			
groundwater relief measures in aquiclude (below excavation level):					
estimated catchment area per groundwater well=			300 m²	each	
Cut-off-wall				**Temperature profile**	
depth:	17.5m	below ground level		low temperature 80° – 30 °	
Embanked excavations: V2, V2, V1				V3	
possilble slope angle:	*minimal slope angle: 26.6°!*			*slope angle V3*	
excavation depth ≤	15.0m	-> ß =	33.7°	-> ß =	26.6°
excavation depth >	15.0m	-> ß =	30.5°	embankment & excavation	

Construction site		
urban dedication	3	1 = agricultural land 2 = industrial and commercial land 3 = residential area
available site area (if known):	150,000 m²	V1, V1a, V1b, V1c, V2a, V2b, V2c, V2.1a, V2.1b, V2.1c, V2.2a, V2.2b, V2.2c, V3a, V3b, V3c
-> possible construction types:		

Embankment (above ground level) (excluding V3)			
dam height: H=	15.0 m	slope angle = 2:3	33.7°
width of dam crest: B =	5.0 m	*Embankment bulk material*	
freeboard height: h=	1.0 m	below dam crest	

Cover-construction		
requirements regarding the load bearing capacity of the construction:		3
1= low:	non usable (only walkable) danish system	
2= high:	fully accessible (payload **3.5** kN/m²)	
3= high:	fully accessible (payload **7.5** kN/m²)	

Wall sections for insulation							
select: 1 = yes, 0= no insulation							
section I:	0	above ground level (embankment, wall and dam base berm)					
section II:	0	below ground to depth	*t*= 15,0m	*gw-level*	VA-steel		PP
section III:	0	below depth *t*, to bottom slab		material	nein		ja
section IV:	0	bottom slab			ja/nein		

Storage cubatures to be compared (V1 must be ≤ 200.000m³)		
Variant a	**Variant b**	**Variant c**
500,000 m³	1,000,000 m³	2,000,000 m³

Figure 29: Example of input data sheet

Each construction type is presented in a separate data sheet. For each construction type a pre-calculated storage efficiency is used, defined by volume, temperature profile, excavation depth and thermal insulation based on preliminary simulations using standardized seasonal load profiles.

5.1.2 Output data

A separate cost calculation sheet is created for each type of construction (see Figure 30). Individual details of the construction can be added there. In a first step, the geometric dimensions and relevant masses of the respective construction are determined to calculate the costs. In a second step, costs are assigned to the quantities using the unit price method commonly used in the construction industry, thus resulting in the total construction costs. The unit prices are based on empirical values from projects that have already been completed.

In relation to the specific volume of the storage, the specific construction costs in €/m^3 are shown. Taking the storage efficiency into account, the resulting effective construction costs €/m^3 are also displayed.

Modifiable parameters

- Excavation depth can be selected specifically for each selected volume.
- The dimensions of the base plate (concrete slab) can be entered individually.
- The dimensions of the above ground retaining wall angle can be adapted to the local conditions
- The efficiency factor is determined from a separate database and taken into account when calculating the effective costs. It depends on the construction type, the temperature profile, the volume, and the selected thermal insulation.

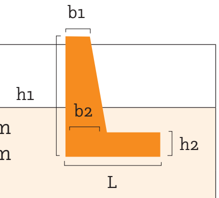
Output parameters

- The main cost contributions are displayed at the bottom which comprise of:
  - land costs
  - site overheads
  - civil engineering works
  - reinforced concrete
  - construction
  - earthworks
  - storage linings
  - floating cover
- The total and the effective costs per m^3 storage volume are also shown.
- A graphic shows the percentage cost breakdown.

Variant 2	Deep pit (square layout); no compensation tank		
	Variant 2a	Variant 2b	Variant 2c
total storage-volume as built	500,000 m^3	1,000,000 m^3	2,000,000 m^3
excavation depth (below ground level)	20 m	30 m	40 m
side length storage bottom	61 m	71 m	92 m
	Goal seek	*Goal seek*	*Goal seek*
side length storage top	145 m	189 m	244 m
width of dam base berm:	4.0 m	4.0 m	4.0 m
depth of lower berm:	10.0 m	15.0 m	20.0 m
lower berm width:	4.0 m	4.0 m	4.0 m
thickness of bottom slab:	0.60 m		

Figure 30: Example output data sheet for specific construction type (deep pit)

embankment wall (at dam crest):			
height (compl., incl. fundation): h1 =	**15.0 m**	length of fundation: L = hight of fundation: h2 =	8.0 m 2.0 m
top wall-width: b1 =	**1.0 m**		
bottom wall-width: b2 =	**2.0 m**		

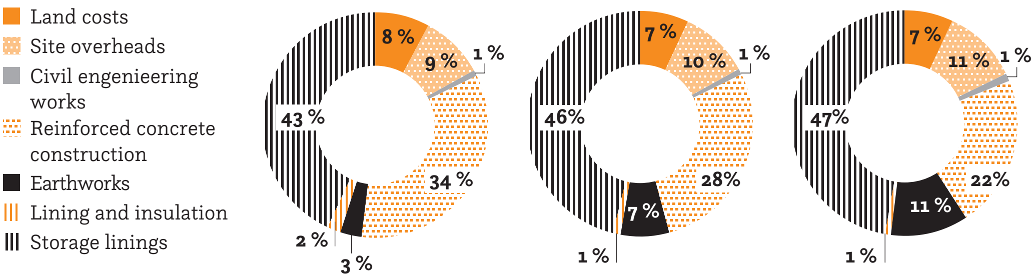


wall-construction type per section:	above ground (embankment):	D - inside insulation - PP	*not insulated*
	below ground to depth *t*:	sealing only - PP vertical	*not insulated*
	below depth *t*:	sealing only - PP	*not insulated*
	bottom slab:	sealing only - PP	*not insulated*

Results

	Variant 2a	Variant 2b	Variant 2c
total storage-volume	**500,000 m³**	**1,000,000 m³**	**2,000,000 m³**
storage efficiency	**69.32 %**	**74.02 %**	**78.72 %**
effective storage volume	**346,619 m³**	**740,242 m³**	**1,574,494 m³**
storage volume above ground	293,953 m³	500,968 m³	833,850 m³
land use	40,362 m²	60,106 m²	90,030 m²
excavation volume	206,047 m³	499,032 m³	1,166,150 m³
dam building	163,253 m³	207,073 m³	261,410 m³
excess mat. / shortcoming	42,793 m³	291,959 m³	904,740 m³
cover surface	20,997 m²	35,783 m²	59,561 m²
wall surface	25,191 m²	37,527 m²	55,231 m²

Total construction costs	**€ 49,718,190**	**€ 79,524,581**	**€ 129,604,875**
relative CC (total)	**99 €/m³**	**80 €/m³**	**65 €/m³**
relative CC (effective)	**143 €/m³**	**107 €/m³**	**82 €/m³**
land costs	€ 4,036,173	€ 6,010,591	€ 9,003,037
site overheads	€ 4,428,610	€ 7,608,330	€ 13,682,127
civil engineering works	€ 574,242	€ 713,670	€ 886,559
reinforced concrete construction	€ 16,835,000	€ 22,029,561	€ 28,875,181
earthworks	€ 1,681,649	€ 5,579,379	€ 14,817,897
storage linings	€ 829,897	€ 1,227,097	€ 1,826,402
floating cover	€ 21,332,620	€ 36,355,954	€ 60,513,672
linings base only	*€ 74,182*	*€ 101,289*	
linings walls only	*€ 328,457*	*€ 429,376*	*€ 554,515*



5.2 Case study performance results: City A

With the intended storage capacity and loading profiles obtained, the next step is to evaluate which storage design is most cost-effective for the location in mind. For the target volume of 1,200,000 m³, a parameter study was carried out in the cost tool to estimate the specific investment costs and corresponding land use for all considered storage geometries for a range of different storage depths. Figure 31 gives an overview of the specific storage cost curves for each applicable storage design, assuming a stainless-steel liner, fully accessible cover both insulated (lid thermal insulation and wall thermal insulation down to depth of aquiclude) and non-insulated (lid thermal insulation only) cases. In all cases, the maximum permitted dam height of 15 m was chosen as this led to the lowest costs for each design due to maximum reuse of excavated soil. The following boundary conditions (see Table 5) for land use and hydro-geological properties were assumed for both use cases:

Boundary condition	Value	Comment
Land use cost	100 €/m²	Residential/Inner city area
Depth to groundwater	5 m	
Depth to aquiclude	15 m	10 m groundwater layer thickness

Table 5: Location boundary conditions for City A and City B

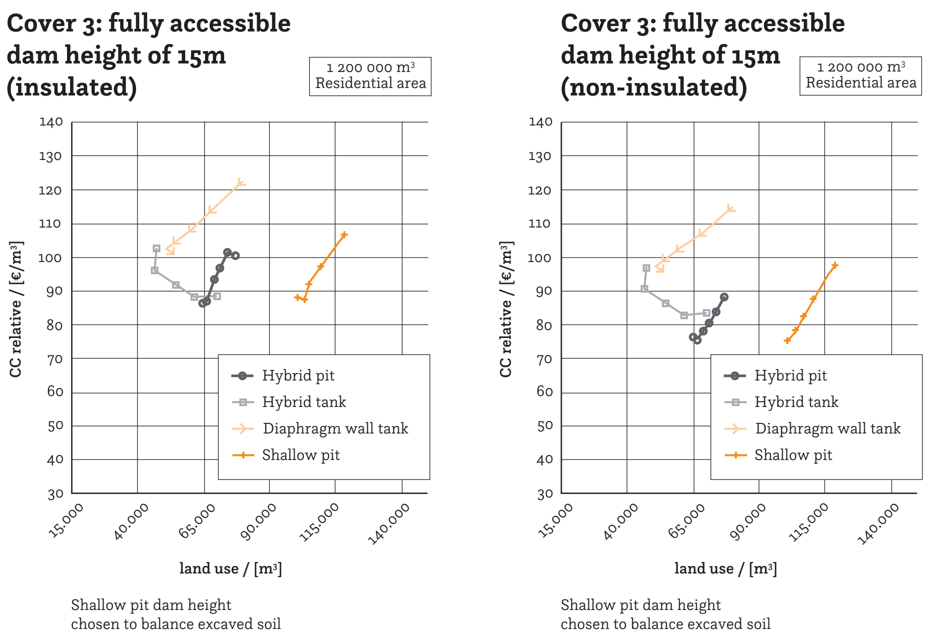


Figure 31: LTES costs vs land use - 1.2 million m3, fully-accessible cover, VA-Liner. With wall thermal insulation down to aquiclude depth (15 m) (left), with no wall thermal insulation (lid only). (right)

The comparison shows that diaphragm wall tank design is significantly higher in costs than the other three geometries for such boundary conditions – the shallow pit delivers costs in the same range as the hybrid pit but with significantly higher land use. The hybrid pit and hybrid tank geometry were found to deliver similar investment costs and land usage at their respective cost-optimal depths. The **hybrid pit** design was selected as the geometry of choice for both insulated and non-insulated variants while it delivered the lowest overall investment costs. The cost-advantage of the hybrid pit over the hybrid tank geometry is more significant for the non-insulated cases.

Figure 32 shows an overview of the storage performance at system level regarding heat mix compared to the reference case with no LTES; Figure 33 shows the total estimated CO_2 emissions for these configurations. The emission factors applied can be found in Appendix B.

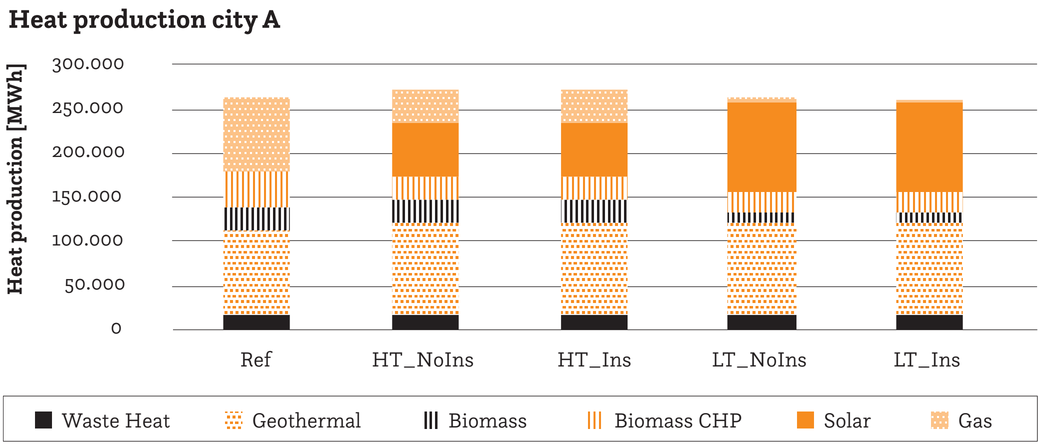


Figure 32: Comparison of heat production for HT and LT systems for both insulated (Ins) and non-insulated (NoIns) LTES -1,200,000 m³

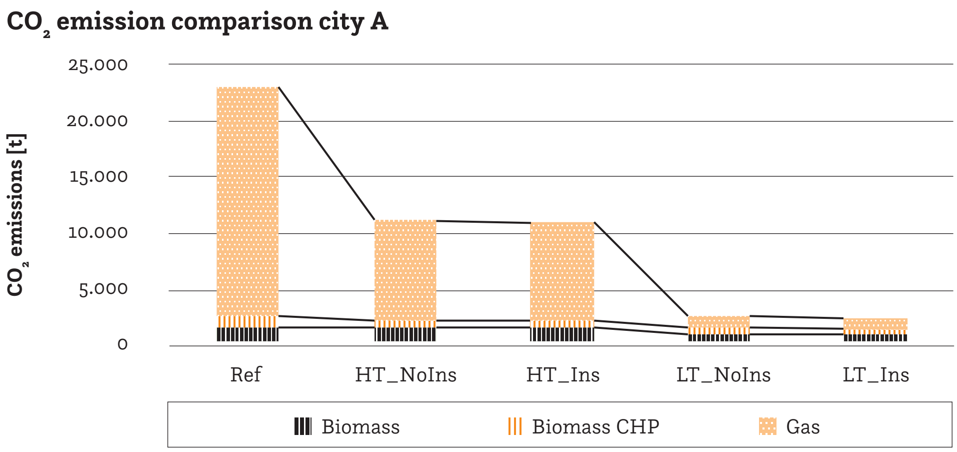


Figure 33: Comparison of CO_2 emissions for HT and LT systems for both insulated and non-insulated LTES – 1,200,000 m³

The integration of the LTES into the HT system enabled a reduction in the share of gas from 28 % in the reference case down to 13 % with the thermal losses of the storage considered. For this system there was a certain degree of post heating needed in order to maintain the discharged heat at the required supply temperature of 90°C (approximately 20 % of the total discharge). Post heating was covered by biomass when there was sufficient capacity available, otherwise the gas boilers were used. The LT cases enabled a much higher share of solar thermal due to the larger effective storage capacity, thus reducing the share of gas down to only 0.2 % of total heat demand.

To get an overview of costs, Figure 34 includes a breakdown of the estimated total investment costs plus the specific costs for each LTES variant.

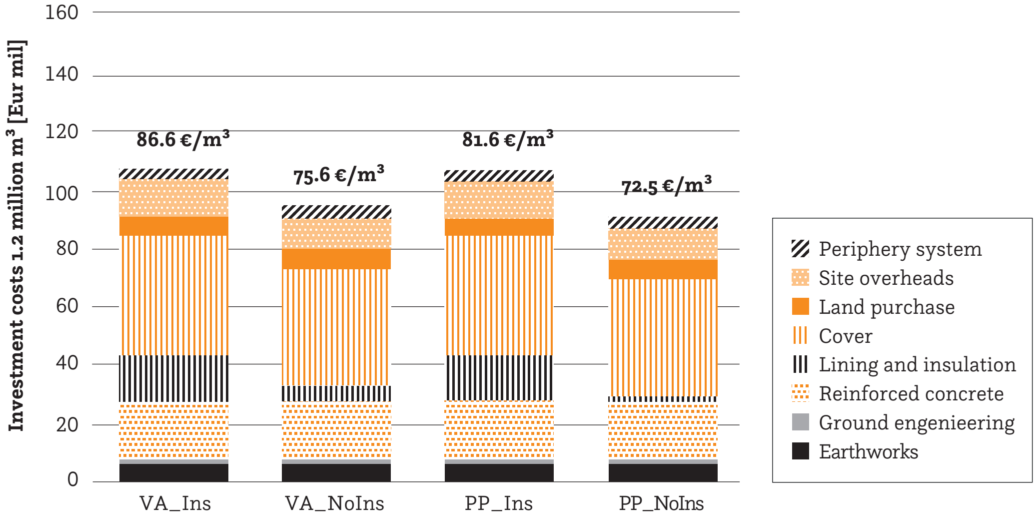


Figure 34: Investment cost comparison - 1,200,000m³ LTES (Hybrid Pit, Fully Accessible Cover). On top of each variant, the specific costs are given.

Newly developed PP liners in the project have shown estimated lifetimes more than 50 years at temperatures up to 80 °C with significantly lower specific costs than stainless steel – PP liners were therefore chosen for the LT cases. For the high temperature cases, the PP liner life time is expected to reduce down to 31-33 years and therefore the stainless-steel (VA) liner is chosen to ensure a comparable lifetime of 50 years, too. Table 6 includes a projection of the main storage performance parameters including the respective levelized costs of storage (LCOS) and storage efficiencies. The methodology for the evaluation of the LCOS used here can be found in Appendix C.

Table 6: Main storage techno-economic parameters for 1,2000,000 m³ hybrid pit, fully accessible cover LTES

	HT_Ins	HT_NoIns	LT_Ins	LT_NoIns
LCOS	92.5 €/MWh	84.0 €/MWh	55.0 €/MWh	50.1 €/MWh
Storage cycles	1.45	1.42	1.36	1.35
Energy charged	65 GWh	64.6 GWh	100.3 GWh	99.6 GWh
Energy discharged	59.43 GWh	58.136 GWh	94.8 GWh	94.2 GWh
Thermal losses	4.37 GWh	5.24 GWh	3.3 GWh	3.9 GWh
Energy difference	1.2 GWh	1.2 GWh	2.16 GWh	1.52 GWh
Storage Efficiency ($\eta_{TES,sto}$)	89.5 %	87.4%	95.3 %	94.3 %

The LCOS are significantly higher for the HT system at approximately 92 €/MWh for the HT insulated case compared to 55 €/MWh for the LT insulated application. The non-insulated case sees a reduction of about 8.5 €/MWh and 5 €/MWh for the HT and LT cases respectively. Despite the savings in omitting thermal insulation – thermal insulation will often be necessary in order to protect the groundwater from overheating and is therefore unavoidable, see section 7.2.4. The number of storage cycles plays a key role in the levelized cost of storage – the application in this scenario was for a predominantly seasonal storage rather than a short-term buffer and therefore the obtained storage cycles is only in the range of 1.35-1.45 depending on thermal losses and temperature levels of the storage. For the HT cases, the levelized costs are at the higher end of the range and further cost optimisation of materials may be necessary in order to make a seasonal-storage-only application more economically feasible – another approach to do so would be to consider a non-usable cover design as will be outlined in one variant for City B.

5.3 Case study performance results: City B

As with City B LTES scenarios, the cost tool was used to aid with the selection of the most cost-effective storage design based on the given hydrogeological and DH boundary conditions. For smaller volumes in the range of 100,000 m³ an additional buried cylinder design is also deemed feasible and is also included in the comparison with the cost tool. Figure 35 below includes a parameter study with insulated and non-insulated LTES designs with a stainless-steel liner and fully accessible cover for a range of different storage depths to see the influence on specific costs and land use. In all cases, a dam height of 5 m showed the best cost performance – larger than 5 m would require an import of new soil to build the whole dam.

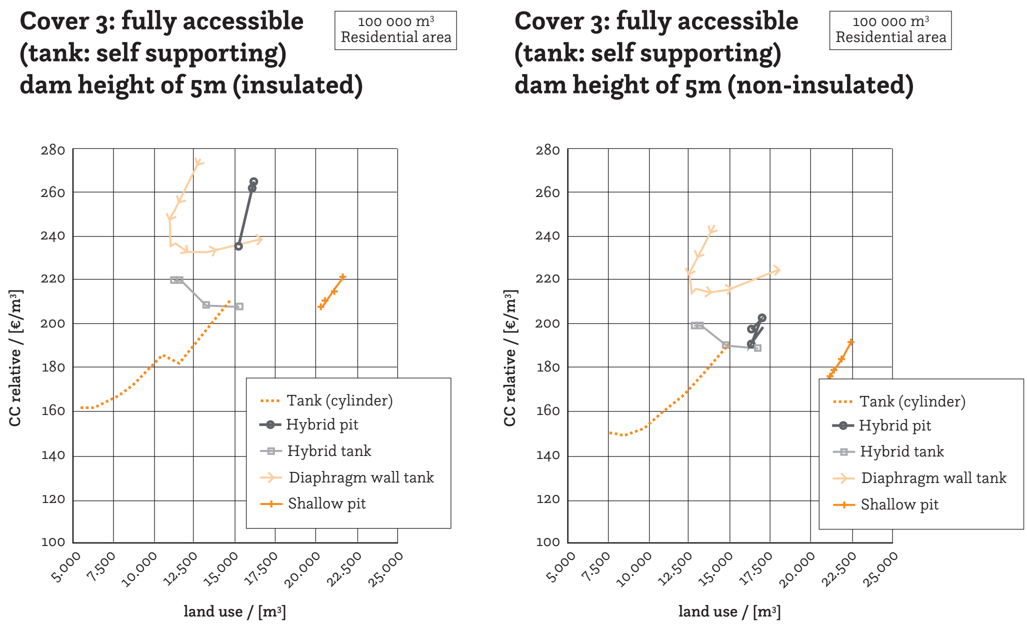


Figure 35: LTES costs vs land use 100,000 m³ fully-accessible cover with stainless steel liner. With wall thermal insulation down to aquiclude depth of 15 m (left) and (right) with no wall thermal insulation (only lid insulated)

Figure 36 and Figure 37 include a breakdown of the performance of the storage on the overall system heat mix and CO_2 emissions for both HT and LT systems.

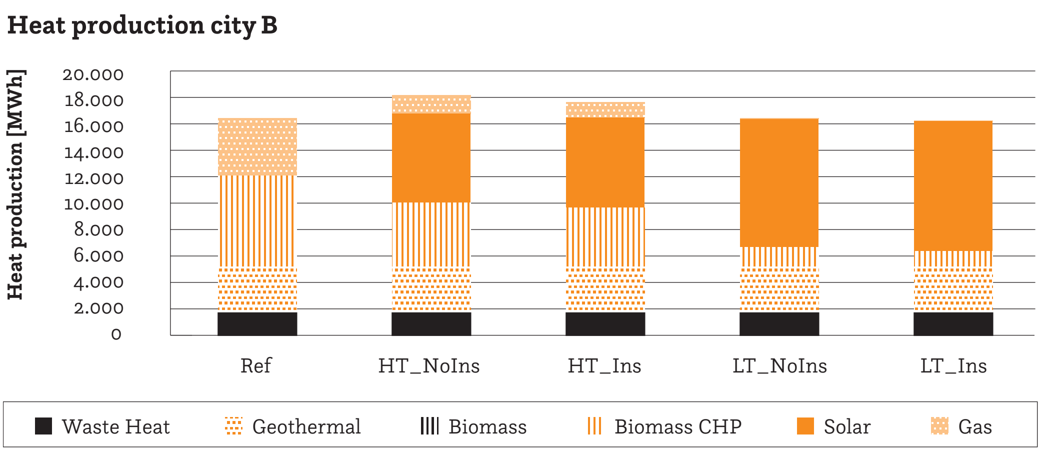


Figure 36: Comparison of heat production for HT and LT systems for both insulated (Ins) and non-insulated (NoIns) LTES – 100,000m³

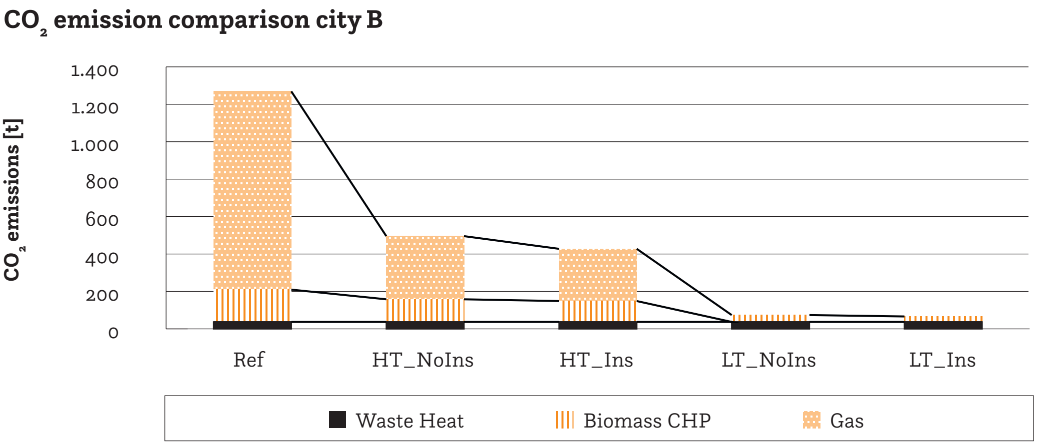


Figure 37: Comparison of CO_2 emissions for HT and LT systems for both insulated and non-insulated LTES – 100,000m³

The benefits of the LT system over the HT here are again very apparent, with the LT enabling a reduction of total share of heat from gas from 28 % in the reference case to approximately 0.2 %, allowing for a complete phase out of the gas boiler. The HT cases, with a smaller effective storage capacity and significant post heating, managed a reduction of gas down to approx. 8 %. To get an overview of costs, Figure 38 and Table 7 include a breakdown of the estimated investment costs for each LTES variant.

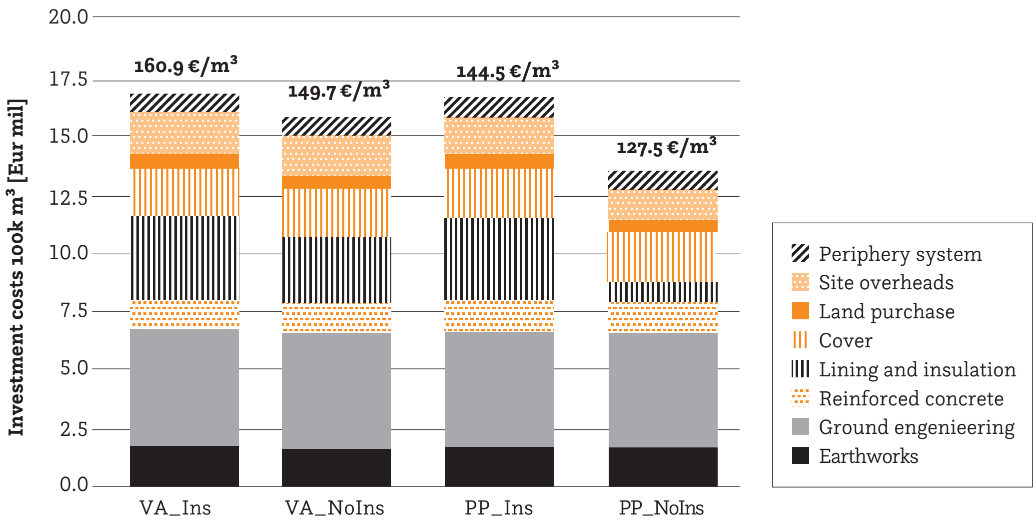


Figure 38: Investment cost comparison - 100,000m³ (buried cylinder tank, fully accessible cover LTES)

As before, polypropylene liners were selected for the LT cases and stainless steel for the HT cases to enable a comparable storage lifetime to benchmark the LCOS values. The specific investment costs calculated here are significantly higher than those of the larger deep pit LTES demonstrated in City A, with the insulated design with stainless steel liner being approximately 160 €/m³ - more than double the specific costs compared to that in City A. Table 7 includes a projection of the main storage performance parameters including the respective levelized costs of storage (LCOS) and storage efficiencies.

	HT_Ins	HT_NoIns	LT_Ins	LT_NoIns
LCOS	138.6 €/MWh	138.7 €/MWh	90.6 €/MWh	79.3 €/MWh
Storage cycles	1.66	1.58	1.41	1.35
Energy charged	6.6 GWh	6.5 GWh	8.8 GWh	8.65 GWh
Energy discharged	5.8 GWh	5.5 GWh	8.2 GWh	7.9 GWh
Thermal losses	0.66 GWh	0.877 GWh	0.477 GWh	0.713 GWh
Energy difference	0.14 GWh	0.12 GWh	0.12 GWh	0.037 GWh
Storage efficiency $\eta_{TES,sto}$)	81 %	74.8 %	91.7 %	87.7 %

Table 7: Main storage techno-economic parameters for 100,000m³ fully accessible cover LTES

The high specific costs are reflected in the LCOS with the HT cases being in the range of 139 €/MWh. The LT cases are significantly more cost effective due to the use of PP liners and overall higher discharged heat from the storage over the year. Efficiencies are overall lower than the 1,200,000 m³ cases as expected due to the higher surface to volume area – nonetheless, the chosen cylindrical volume with a depth down to 50 m gives a considerable high efficiency for its volume with the insulated cases in the range of 80 % and 92 % for the HT and LT cases respectively. Nonetheless, for a trafficable cover with seasonal operation, the design is far from economically feasible. A storage design with reduced costs at the expense of having a non-usable cover was also evaluated for the four variants above.

The same comparison across all designs for a non-usable cover showed that the shallow pit design with a comparable slope to those of LTES already constructed in Denmark would be the most economically feasible design so long as excavation can go deeper than the ground water level by including a cut-off wall and sufficient wall thermal insulation in the region of the ground water. With these additions, the optimal sizing was found to be with a depth of 22 m and a dam height of 6 m for the shallow pit. Figure 39 and Table 8 include a breakdown of the investment costs for each variant in this case.

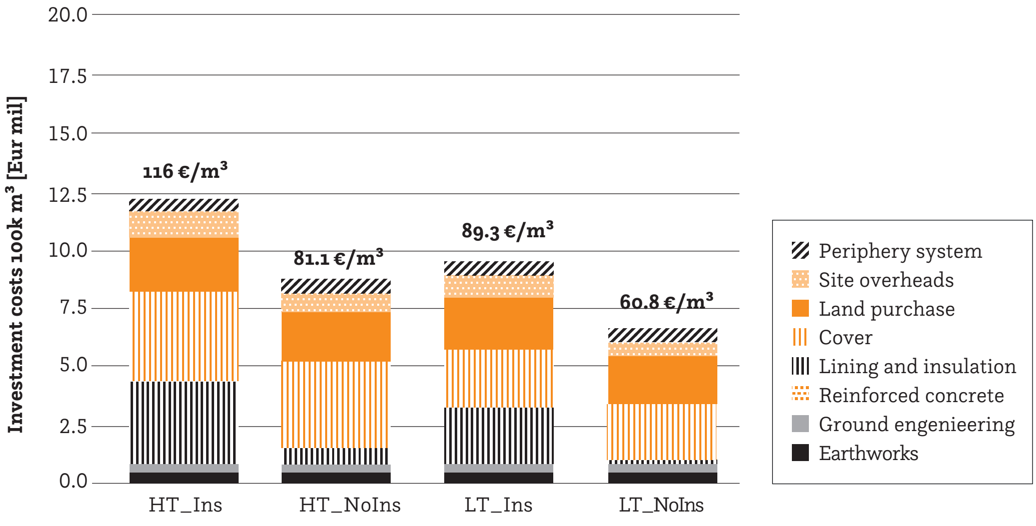


Figure 39: Investment cost comparison - 100,000m³ LTES – (shallow pit) non-usable cover

The specific costs are still comparably high for the HT applications, largely due to the high surface area required for thermal insulation and lining – the LT variants can have significant cost savings by reducing liner and cover costs accordingly. The non-insulated case is in the range of 61 €/m³ including land purchase. If land purchase and periphery costs (heat exchangers, piping, water sourcing and treatment) are omitted, the specific costs of this case are in the same range as those of realised Danish LTES in the 100,000 m³ range (6).

Table 8 includes a comparison of the LTES yearly techno-economic performance for the shallow pit design.

	HT_Ins	HT_NoIns	LT_Ins	LT_NoIns
LCOS	107.1 €/MWh	82.4 €/MWh	58.5 €/MWh	43.4 €/MWh
Storage cycles	1.61	1.52	1.39	1.34
Energy charged	6.6 GWh	6.5 GWh	8.8 GWh	8.65 GWh
Energy discharged	5.6 GWh	5.3 GWh	8.1 GWh	7.8 GWh
Thermal losses	0.825 GWh	1.05 GWh	0.596 GWh	0.856 GWh
Energy difference	0.175 GWh	0.15 GWh	0.1 GWh	0.0 GWh
Storage efficiency ($\eta_{TES,sto}$)	76.3 %	69.7 %	89.7 %	85.2 %

Table 8: Techno-Economic KPI comparison for a 100,000 m3 LTES, shallow pit, non-usable cover design.

In general, thermal losses are approximately 20-25 % more than the equivalent cases with a cylindrical tank. It should be noted that in practice, thermal losses can be significantly higher than these simulated values due to the influence of moving ground water.

It also must be noted that in general, groundwater heating by underground structures is limited by law and the maximum allowed increase of temperature is very limited. Therefore, in praxis, only LTES variants with thermal insulation will be applicable, restricting the possibilities for lower-cost, non-insulated concepts. Furthermore, when considering the level of costs for the LTES showed here, we must keep in mind that costs are based on building materials and techniques for conventional deep construction techniques. Both intrinsic cost uncertainties and cost reduction potential through further building techniques and building practices development are high. This will be further highlighted in the Outlook.

6 Materials development

Two important components for a large thermal energy storage are the liner and the wall material. For an application in a LTES, the materials for these components should be resistant to water and water vapour of high temperatures, up to 95 °C. For liners, either polymeric sheets or stainless steel are possible. In the project, polymeric sheets have been established and continuously improved as to the long-term durability, while for concrete wall materials first investments in the long-term behaviour under high-temperature, high-moist conditions were done.

6.1 Development of liner materials

Currently, polyethylene (PE) liner materials are well established for pit storages with maximum operating temperatures of up to 80 °C. As shown in a previous research project (SolPol-4/5), the durability of PE liner materials is rather limited in a temperature range from 80 to 95 °C with lifetime values below 20 years. Hence, in the gigaTES project, a main focus was given to the development of novel polypropylene (PP) liner materials with enhanced maximum service temperatures up to 95 °C (i.e., +15 K compared to established PE liners). Therefore, a commercially available base resin was optimized with advanced stabilizer packages and experiments were performed to determine the global ageing behavior in hot water and hot air (temperatures: 65 to 135 °C in 10 K steps). For accelerated ageing characterization and lifetime prediction a testing methodology based on micro-sized specimen was used. In Figure 40 the endurance times of the best performer PP-HTR (polypropylene high temperature resistant) grade are compared to the commercially available PP-R (polypropylene reference material, which is primarily used for hot water pipe applications. Due to the fact that exposure to hot air was much more critical than in hot water, hot air ageing data are displayed. The numbers depicted in Figure 40 were obtained for 100µm micro-sized specimen taken by CNC milling from 2 mm thick extruded liners. As evidenced in the previous SolPol-2 project, the endurance times of such PP grades at 100µm thickness are about a factor of 2 lower compared to an application relevant liner thickness of 2 mm. At 115, 125 and 135 °C about twice higher endurance times in hot air were obtained for the optimized PP-HTR grade compared to the PP-R reference material. Of high relevance are the endurance time values gathered at lower temperatures. The ageing experiments at 95 and 105 °C are still ongoing. At these temperatures the endurance times of the 100µm micro-specimen made from PP-HTR are exceeding 45.000 hours.

Material	95 °C	105 °C	115 °C	125 °C	135 °C
	Endurance times of 100 µm samples in dry air [h]				
PP-R	32,000	22,000	14,500	6,800	3,300
PP-HTR	> 45,000	> 45,000	32,000	14,000	8,100

PP-HTR:
- >2x better durability than PP-R
- even better behavior in moist air (factor: 1.5x)
- unique behavior in hot water (at 135°C >4x better than in dry air)

Figure 40: Endurance times of 100µm thick specimen made from the reference material PP-R and the optimized grade PP-HTR in hot air at 95 to 135 °C

For lifetime assessments, two temperature variants, two thermal insulation variants and two volume variants (HT: 60-90 °C; LT: 35-80 °C; (un-)insulated, 100k vs. 1200k m^3) were considered. The temperature load profiles shown in Figure 41 were calculated in a numerical simulation of the storages based on the case studies. The temperature profiles were input in a ultimative damage based lifetime prediction program model, that uses the results of the accelerated ageing tests of the PP liner. For the PP-HTR liner, lifetime in the range of 31 to 35 years were determined for the HT-storage types. Slightly lower values (<5 %) were obtained for insulated and larger storages (100 k vs. 1,200 k m³). The significantly increased durability compared to the PP-R reference material or to well established PE liner grades is of high relevance due to the fact, that many storages currently under conception or development, are designed for high temperature loading profiles up to 90 °C or higher. For well-established low-temperature LTES with operating temperatures in the range from 35 to 80 °C, the lifetime values of the optimized PP-HTR liner were significantly exceeding 50 years.

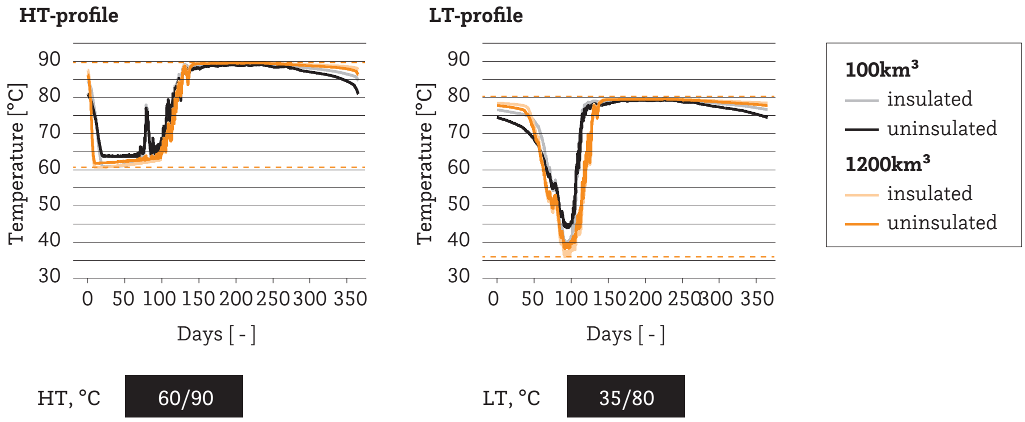


Figure 41: Annual temperature distributions of for high- and low temperature storages (HT; LT) of different size (100k and 1200k m³) and with or without thermal insulation; these profiles were considered for assessment of liner lifetime.

Due to the fact that the liner is exposed to ultraviolet light (at least during installation), PP materials with different UV-protecting pigments and stabilizer packages were also investigated. Special attention was given to the weathering in comparison to hot air ageing behavior. The results clearly showed that optimum stabilizer packages under hot air conditions are poorer in performance under artificial weathering. For the best-performing PP-HTR liner grade, the avoidance of a special pigment was essential. Based on these results, the raw material supplier has commercialized a reference PP-R grade which allows for both, good hot air and weathering resistance.

In addition to the development of liner materials, welding techniques and the effect of welding on the quality of liner materials were also assessed. Established hot wedge welding techniques were examined for novel PP liners varying the hot wedge temperature (from 320 to 410°C). In Figure 42 the approach for hot welding and preparation of micro-sized PP specimen for ageing testing is depicted.

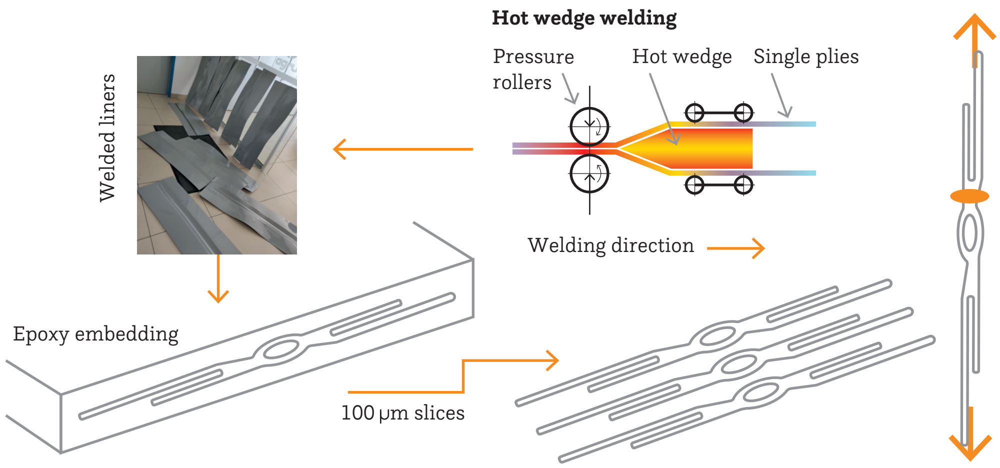


Figure 42: Method for hot wedge welding of PP liners and preparation of micro-specimen for ageing testing.

Micro-sized slices were taken by CNC-milling from welded liners embedded in stiff epoxy blocks. The sliced micro-specimens were aged in hot air at 95, 115 and 135 °C for up to 12,000 hours. Aged specimens were characterized by infrared transmission spectroscopy, differential scanning calorimetry and tensile testing. The ageing indicators including phenol index, oxidation temperature, carbonyl index and strain-at-break were assessed in comparison to unwelded micro-specimen. Hot wedge welding and the wedge temperature had a negligible effect on these ageing indicators (see Figure 43).

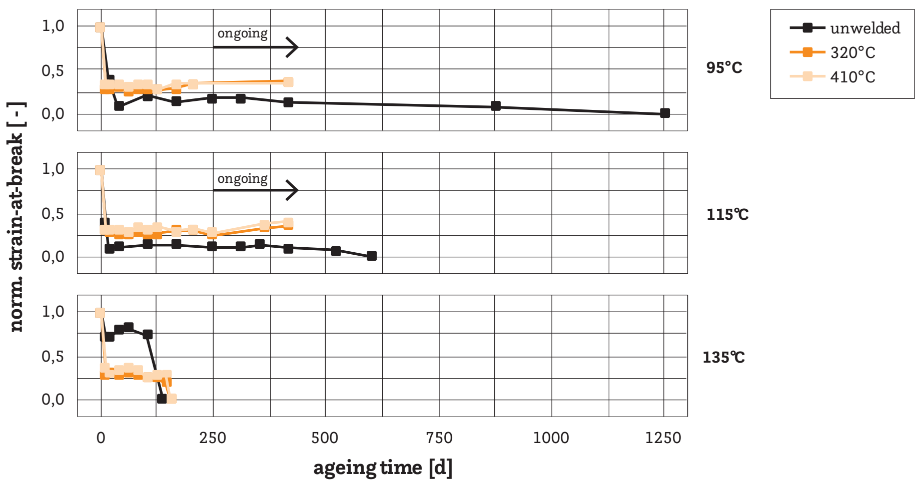


Figure 43: Normalized strain-at-break as a function of hot air ageing time of micro-specimen taken from unwelded liners and PP-R welded at a hot wedge temperature of 320 and 410 °C.

6.2 Ageing behaviour of concrete materials

While polymeric liner materials are well established in the LTES market and are allowing for performance enhancement, so far, no systematic ageing characterization of concrete as a potential liner material has been performed. Hence, functional concrete grade (such as watertight concrete) and well-processable concrete grades (e.g., diaphragm wall concrete; sprayed concrete) were investigated for the first time as to their long-term performance in hot water at elevated temperatures (95 and 135 °C). Therefore, a test facility based on stainless steel autoclaves was concepted and implemented. Cylindrical concrete specimens were manufactured and exposed in hot, pressurized water for up to 6 months. In Figure 44 the concept for long-term testing of cylindrical concrete specimen in hot water is depicted. As shown in Figure 45, increasing compressive strength was only discernible for water-tight concrete. Sprayed and diaphragm wall concrete revealed especially at 135 °C a significant drop in compressive strength. At 95 °C, indications for degradation were ascertained for sprayed concrete.

To explain the loss in compressive strength of sprayed and diaphragm wall concrete, detailed morphological analysis was performed. By examination of vacuum fluorescent epoxy impregnated thin concrete slices a significantly increased capillary porosity was detected for sprayed and diaphragm wall concrete exposed in hot water at 135 °C. Further microscopical phase analysis confirmed the formation of secondary sulfate phases (anhydrite, gypsum) at 135 °C (not at 95 °C) and a significant dissolution of cement particles at 135 °C. To evaluate the hypothesis of change in phase stability of hydrated cement with increasing storage temperature, micro-X-ray-fluorescence-analysis (µXRF) was carried out. A temperature dependent depletion of sulfur in the cement stone and precipitation of sulfates in the pores was ascertained for sprayed and diaphragm wall concrete, which are based on sulfur containing concrete formulations. In contrast, sulfur depletion at 135 °C of water-tight concrete based on C_3A (Tricalciumaluminat) free cement was rather small and uncritical.

Testing concept

Formulations:
- slit wall concrete
- white trough concrete
- sprayed concrete

Ageing conditions:
- hot water: 95, 135°C
- cylinders in autoclaves
- intervals: 1, 3, 6 month

Characterization:
- compression test
- morphological analysis

Specimen:
- cylinder:
  diameter & height: 5cm

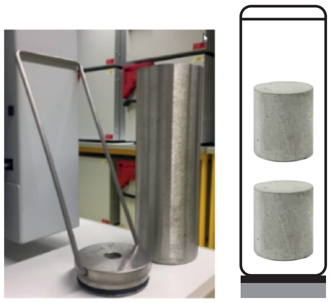
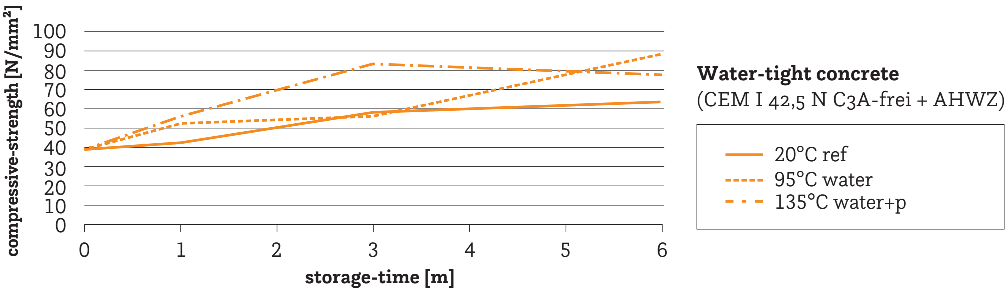
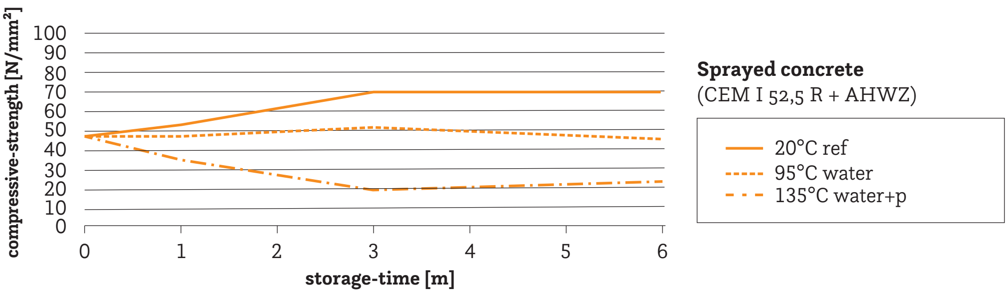


Figure 44: Concept for long-term testing of cylindrical concrete specimen in hot water.





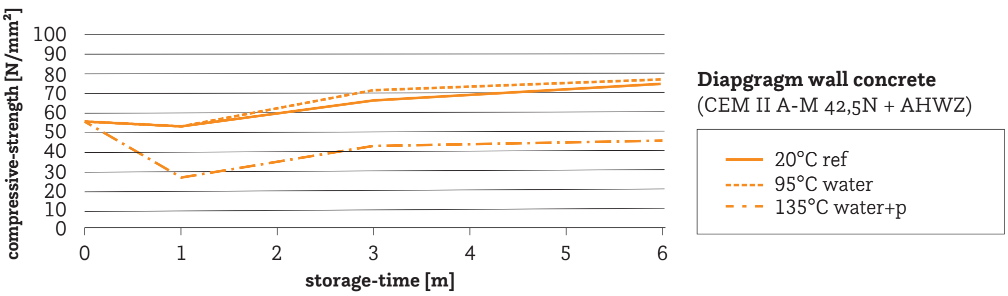


Figure 45: Compressive strength of watertight, sprayed and diaphragm wall concrete as a function of storage in water at 20, 95 and 135°C.

6.3 Development of polymer/metal hybrid laminates with gas barrier capability

A drawback of polymeric liner materials is the temperature dependent permeability of gases associated with loss of water heat carrier or enrichment of oxygen. Hence, polymeric/metal-laminates were developed and examined on specimen level. An ageing and permeation testing concept was implemented allowing for more service-relevant assessment of barrier liner laminates, in contact with hot water and air on the surfaces. Therefore, two flanges with CNC-milled pockets and a groove for an elastomeric sealing ring were manufactured.

In between the flanges, barrier liner laminate samples were placed and evaluated by exposure in heating ovens. To deduce the permeation rate, the pockets were filled with a defined mass of water on one side and dry silica gel on the other. After exposure the mass of the wet silica gel was determined. Furthermore, T-peel tests and fracture surface analysis were carried out.

The deduced permeation rate of 6 g/(m² 24h) for PP liner materials was in good agreement with findings from Danish PTES. For the barrier liner laminate a negligible permeation rate with values within the measurement uncertainty were deduced confirming the effectiveness of the implemented barrier liners. For bonding of the aluminum barrier layer to the outer polyolefin (PP or PE) layers, an ethylene copolymer and a polyurethane adhesive were used. A better long-term behavior was ascertained for the ethylene copolymer adhesive with chemical crosslinking capability in hot-humid environment. For an exposure time of more than 6 months at 95°C no significant degradation of the barrier liner laminates was obtained. Finally, preliminary tests in pH9,5-water with sodium hydroxide were performed showing, so far, comparable results to hot water environment. However, it should be mentioned that the NaOH content was dropping significantly within the first days of exposure. Hence, in future studies an open loop system allowing for continuous supply with pH9,5-water should be developed. Moreover, special attention should be given to appropriate design and evaluation of the long-term performance of barrier liner laminate welding seams.

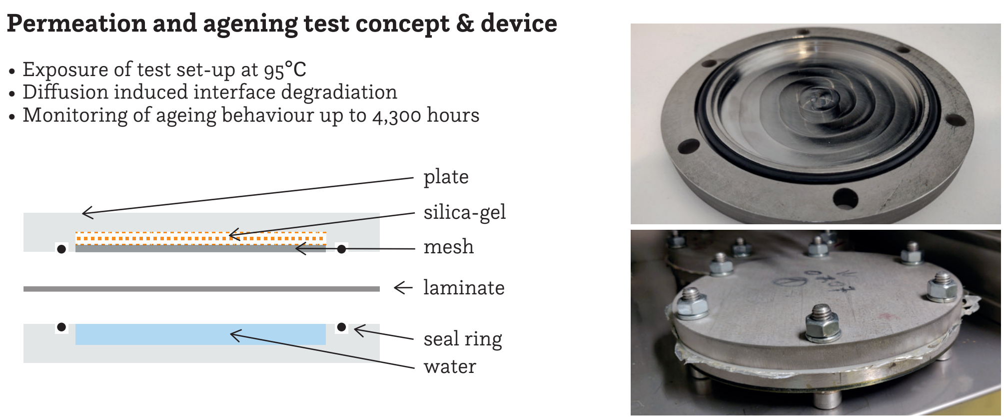


Figure 46: Schematic drawing and implemented device for ageing and permeation testing of barrier liner laminates

7 Influence of design parameters on the storage energy performance

The implementation of numerical models of LTES systems is an important alternative to real experimental investigations, since it allows the evaluation of the influence of different LTES design aspects and boundary conditions on its effective performance as a single element and as part of the district heating system.

As presented in [12] and [3], a "storage level modelling" allows a thorough analysis and optimisation of the TES itself, while a "system level modelling" enables the study of the integration, operation and optimisation of the TES within the DH system. In the first level, tools like COMSOL Multiphysics and ANSYS are particularly effective to define the complex heat (and moisture) transfer mechanisms within the TES itself and between the TES and its surroundings. In the second level, tools like TRNSYS, MATLAB/Simulink and Modelica-based simulation tools are well established in the modelling of large multi-component systems, enabling the definition of the interactions between the different components (i.e., TES, heat sources, consumers) to varying levels of detail. A third modelling level can be further identified when the focus of the analysis is the mutual interaction between the subsurface and the TES (see Figure 47). This modelling approach on the "hydrogeology level" is particularly important in the framework of the environmental impact assessments possibly required for the TES construction.

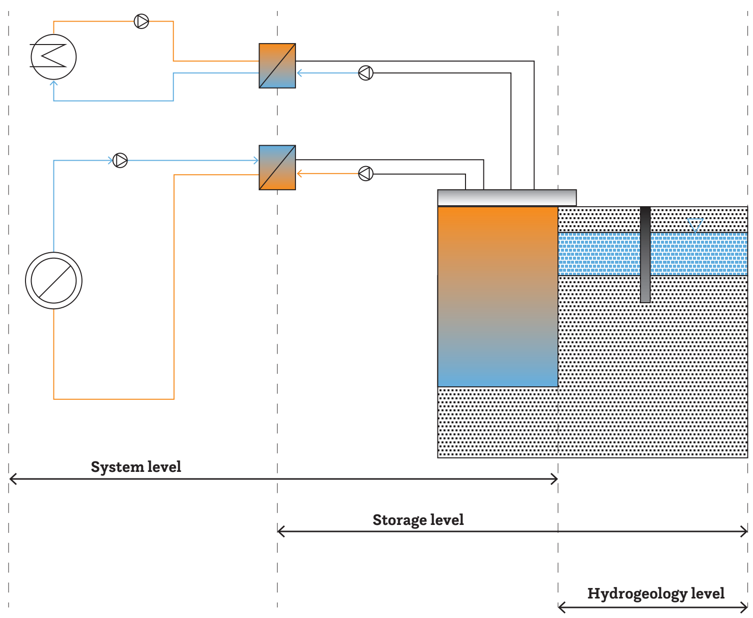


Figure 47: Representation of the three modelling levels [13]: the system-level, the storage- (or component-) level and the hydrogeology-level.

Concerning the performance evaluation of TES systems, numerous indicators, or key performance factors (KPIs), are available in literature and are particularly useful in supporting the decision-making process and in comparing the different TES designs.

Among others, TES discharge efficiency is particularly helpful in defining the ability of a TES to recover the stored energy, and is defined as follows:

$$\eta_{TES,dis} = \frac{Q_{discharge}}{Q_{charge}}$$

Another factor is the energy capacity efficiency, which expresses the ratio between the effective storage capacity of the TES and the maximum theoretical storage capacity. This KPI provides a direct correlation between the annual thermal losses and the maximum storage capacity calculated for that volume:

$$\eta_{TES,sto} = 1 - \frac{Q_{loss}}{Q_{TES\ max.}}$$

An extensive description of the various KPIs available to define the performance of a TES is provided by Dahash et al. in [14]. Herein, the storage capacity efficiency ($\eta_{TES,sto}$) will be used to compare the different TES solutions and will be simply defined as (η).
In this chapter the influence of the main TES design parameters and boundary conditions is investigated with the support of simulation results obtained from the implemented numerical model.

7.1 Implementation of the numerical LTES model

In order to capture the LTES behaviour and define its energy performance, a numerical approach is implemented using COMSOL Multiphysics. The most important feature of this model is its ability to provide a detailed geometric representation of the storage and the surrounding ground in both a 2D and 3D fashion. This characteristic allows the implementation of different geometries such as cylindrical tank, pit, hybrid tank and the introduction of different solutions for the thermal insulation, in terms of distribution, thickness and quality. A thorough description of the methodology adopted to implement this model is provided by Dahash et al. in [14], which further presents its application to a real case study (Dronninglund pit TES, Denmark). The water domain is represented by a 1D line source, vertically divided into n vertical segments with uniform temperature (see Figure 48).

Another important feature of the implemented model is the possibility to include multi-physical aspects, thus enabling the introduction of groundwater (GW), the study of the mutual influence between GW and LTES and the definition of the optimal design of the relative containment structures (i.e. cut-off walls). At this purpose, the ground soil surrounding the LTES is discretized in a finite element (FE) fashion. The 2D representation is useful in case of axisymmetric conditions of the LTES and surroundings, while the application of the 3D is necessary when asymmetries are present (e.g. LTES with rectangular cross section, presence of GW). The possibility to extend the model to both dimensional levels (2D and 3D) is an important advantage since the first enables a remarkable reduction in the computational effort, while the second ensures a deeper understanding of asymmetrical aspects, even if at the cost of more simulation time.

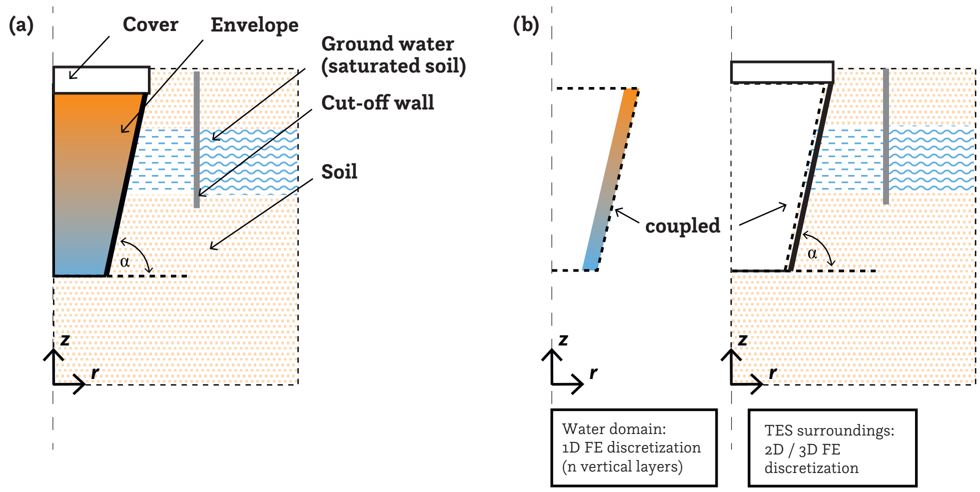


Figure 48: Section of the developed COMSOL TES model. (left)
Distinction of the two domains studied: the water domain and the surroundings (envelope, soil and GW). (right)

An important point in the planning of a LTES is the system where it will operate. Therefore, system aspects, such as DH operation temperatures (HT: high temperature, LT: low temperature), charging and discharging profiles, can be included to provide a more detailed overview of the LTES and its actual role on the system. Although COMSOL Multiphysics proves to be very effective in the detailed study of the LTES as "component", its integration in the district heating system requires the introduction of other elements, i.e. consumers, heat sources and back-up systems, thus determining an increased complexity of the model.
In the end, the implemented model proved to be particularly effective in the description of the "storage" and "hydrogeology" levels, as presented in Figure 47. The following sections provide a general overview of the impacts of ground conditions and LTES design parameters on the effective performance.

7.2 Detailed LTES simulation results

In the following section a general overview of the results of the detailed LTES simulation is provided. In particular, the influence of ground conditions (i.e. presence of GW) on the LTES performance is evaluated for different LTES designs. The presented results and graphs are excerpted from [13].

7.2.1 Impact of ground conditions

Buried LTES have a large interface area between the LTES and the hosting ground, making it important to choose an appropriately selected site upon geological factors (e.g., site's geological conditions, its thermo-physical properties, general hydrogeological and geomechanically properties).

A high thermal conductivity of the soil can strongly influence the LTES performance resulting in inefficient LTES operation. However, a detailed study of the mutual influence between LTES and surrounding environment cannot disregard the porous nature of the soil and the presence of GW. In the last years many countries in Europe have introduced regulations, technical guidelines and recommendations regarding the thermal use of the subsurface: in the case of Austria, the maximum admissible GW temperature is restricted to 20 °C [15]. The LTES influences the GW and vice versa, leading to lower GW quality and to lower LTES performance. These influences can be tackled by several corrective measures, like building a cut-off wall or installing thermal insulation. These measures can be implemented simultaneously, and actually both of them are usually necessary to keep the GW temperature within the temperature limit imposed by the standard (as explained later in the chapter).

An example of the impact of GW flow (u_{GW}) on the LTES performance is presented in Table 9, which shows the thermal losses and efficiency for a tank LTES volume of 2,000,000 m³ in a HT-DH system. In the simulations, the undisturbed GW temperature is assumed to be the annual average of the ambient temperature. The results convey the important finding that the major increase in thermal losses occurs at the sidewalls as the GW flows surrounding the LTES lateral area. From the table, it can be seen that an increase in the groundwater flow leads to a notable increase in the thermal losses compared to favourable geological conditions (i.e., no GW) and a consequent decrease of the storage efficiency.

Q_{loss} [GWh/a]					
u_{GW} [m/s]	top	side	bottom	**total**	η / [%]
0 (no GW)	3.7	1.8	1	**6.5**	91
$2.5e^{-6}$	3.7	4.5	1.1	**9.3**	86.5
$7.5e^{-6}$	3.7	5.3	1.1	**10.1**	85.5

Table 9: Breakdown of total thermal losses and corresponding LTES energy efficiency for a 2,000,000 m³ tank LTES with no thermal insulation on the side walls and bottom and no cut-off wall under different subsurface conditions (excerpted from [13]) .

Figure 49 depicts the subsurface temperature for a tank with 2,000,000 m³ under two different GW conditions. It is clearly seen that the lower GW flow (a) results in higher temperature in farther areas and has influence on the surroundings as the thermal plume size rapidly increases with low velocities.

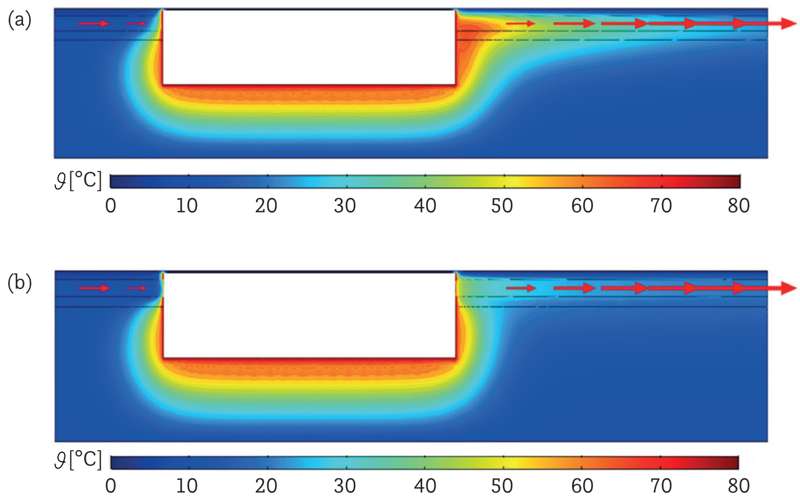


Figure 49: Cross-sectional contour plots for a 2,000,000 m³ tank at the model symmetrical plane (y-z) of COMSOL Multiphysics after 10 years with a GW flow: (a) u_{gw} = 2.5 x 10^{-6} m/s; (b) u_{gw} = 2 x 10^{-3} m/s (excerpted from [13]).

In order to restrict the twofold impact of LTES-GW interaction, numerous engineering techniques can be employed during the construction works. The adoption of an impermeable vertical cut-off wall appears to be particularly effective; however, its location must be properly defined on the basis of the GW flow characteristics. From the simulations, it appears that as the distance of the cut-off walls increases, the thermal losses decrease and, accordingly, the temperature of the GW decreases as well. Moreover, with increasing LTES volumes the thermal losses considerably increase and, thus, the influence of cut-off wall distance might be altered.

7.2.2 Impact of LTES size

The increase in the LTES volume plays a role in increasing the efficiency due to better surface area to volume ratio (SA/V). This concept is shown more clearly in Figure 50 which illustrates the impact of LTES volume, GW velocity and cut-off wall distance (d_{cw}) on the LTES efficiency. The graphs show that the increase in the cut-off wall distance increases the LTES energy efficiency.

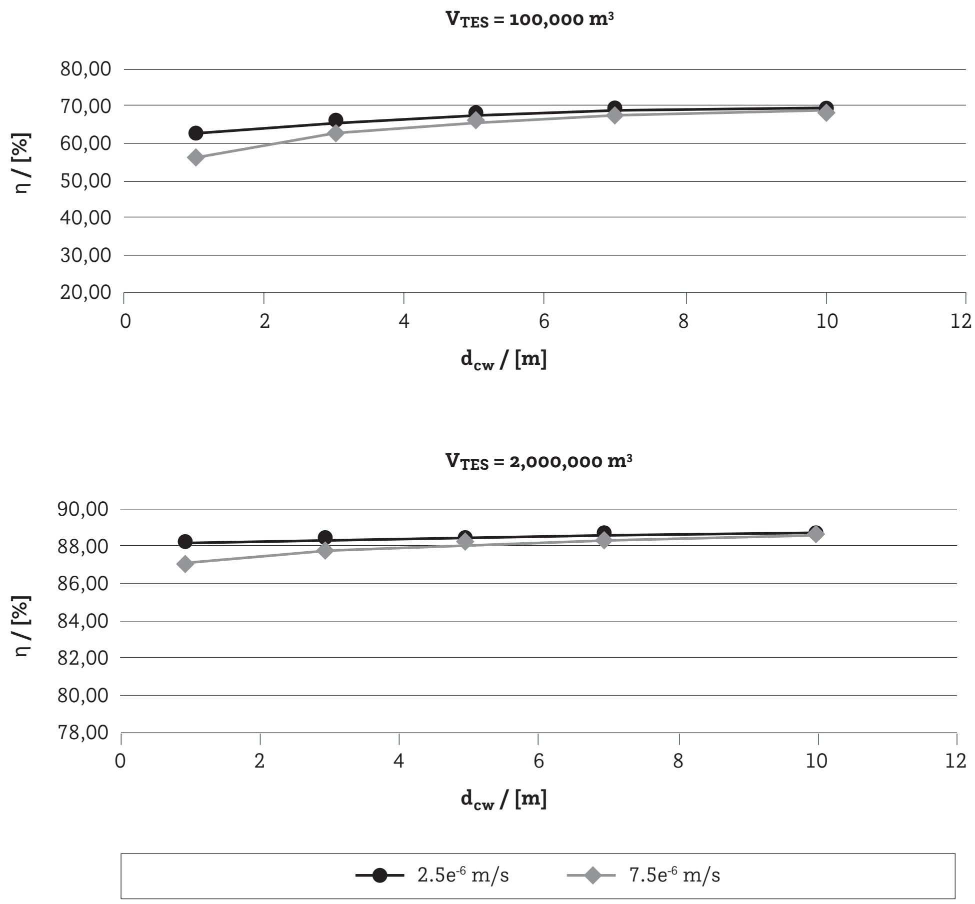


Figure 50: LTES energy capacity efficiency for a buried tank with different volumes (100,000 m^3 and 2,000,000 m^3) under different groundwater flow velocities and cut-off wall distances (d_{cw}) (excerpted from [13]).

In any case, the cut-off wall is also an important measure for larger volumes to prevent overheating of the groundwater. Figure 51 and Figure 52 show the effects of the distance of the cut-off wall in relation to the thermal losses and the downstream temperature for the volumes 100,000 m^3 and 2,000,000 m^3. Although the increased distance between the cut-off walls leads to a minimal improvement in storage efficiency, the effects on the groundwater temperature at the outer surface of the cut-off wall are significant.

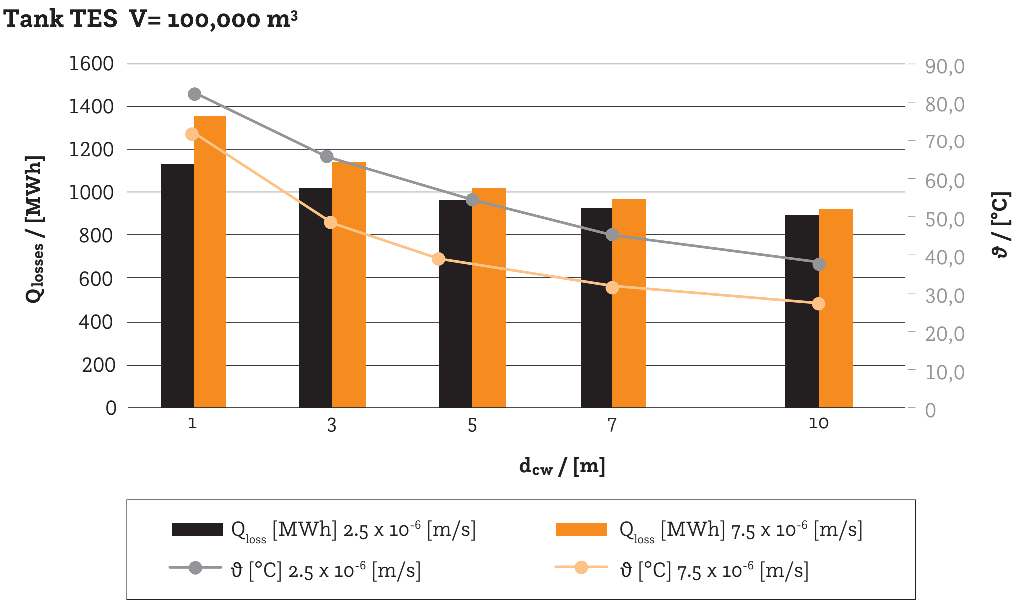


Figure 51: Lateral and bottom thermal losses of a 100,000 m³ LTES (bar chart, primary left y-axis) and the corresponding downstream temperature (line plot, secondary right y-axis) considering different cut-off wall distances (excerpted from [13])

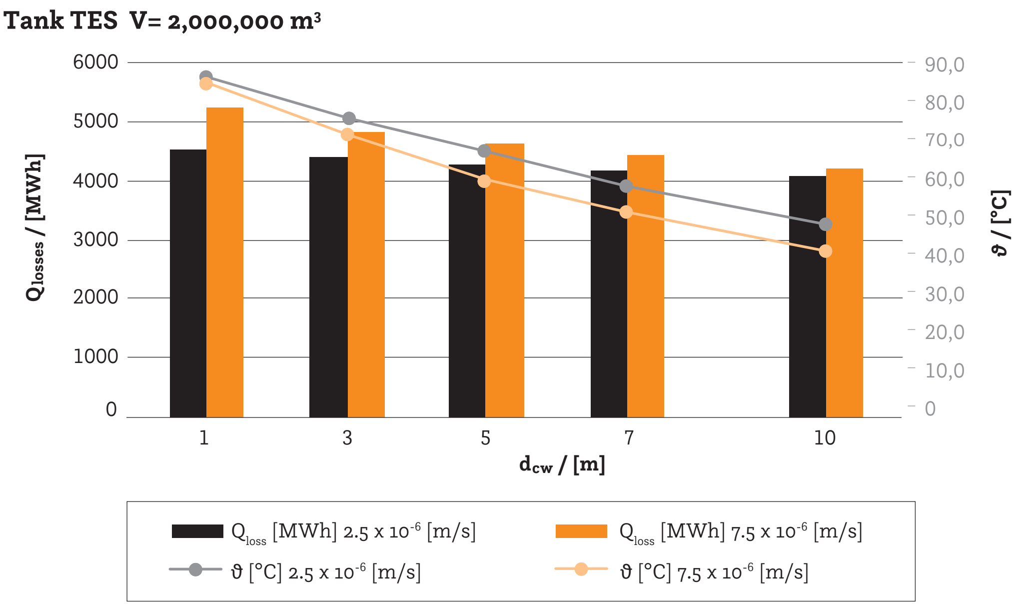


Figure 52: Lateral and bottom thermal losses of a 2,000,000 m³ LTES (bar chart, primary left y-axis) and the corresponding downstream temperatu-re (line plot, secondary right y-axis) considering different cut-off wall distances (excerpted from [13])

7.2.3 Impact of LTES shape

An important consideration for LTES is related to the storage shape: a general recommendation is to keep a small (SA/V) ratio as mentioned in the previous paragraph. In this regard, Figure 53 presents a comparison between a buried tank and a shallow pit (S-pit) with thesame volume of 500,000 m³ considering thermal losses and GW temperature with a flow velocity of (2.5 x 10^{-6} m/s). The results indicate that the shallow pit has higher thermal losses than the tank and, consequently, lower energy capacity efficiency. Yet, the GW temperature is considerably lower for the shallow pit than for the buried tank, , but in both cases a cut-off wall and possibly thermal insulation would be necessary to prevent overheating of the groundwater.

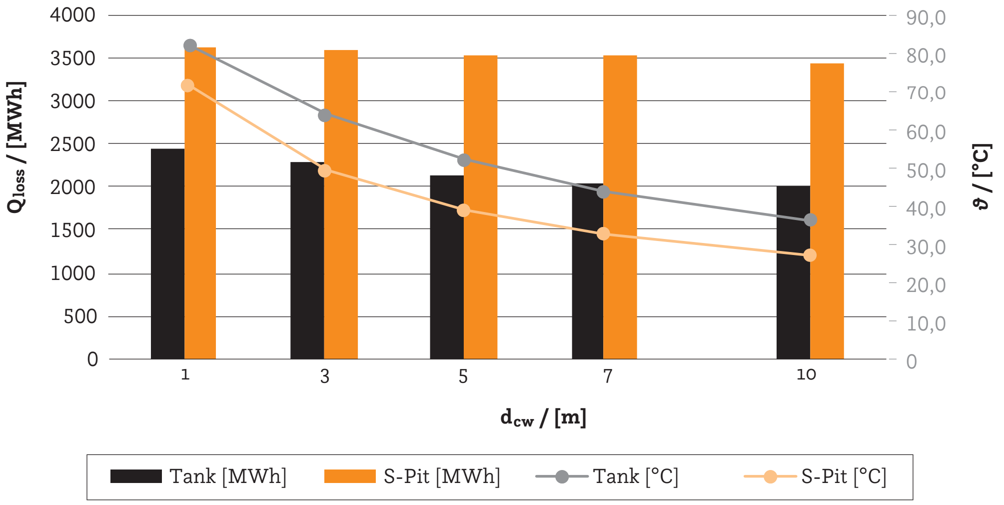


Figure 53: Lateral and bottom thermal losses for HT systems of a 500,000 m³ LTES (bar chart, primary left y-axis) and the corresponding downstream temperature on the outer surface of the cut-off wall (line plot, secondary right y-axis) considering different cut-off wall distances with a groundwater flow velocity of 2.5 x 10^{-6} m/s (excerpted from [13]).

7.2.4 Impact of thermal insulation quality

In addition to the cut-off wall, the adoption of thermal insulation is a key measure to reduce the influence on the ground temperatures. Figure 54 exemplifies that the installation of thermal insulation (1 m thickness) lowers the LTES thermal losses for the realistic range of GW velocities (2.5 x 10^{-6} m/s). Despite this notable decrease, the GW temperature is still higher than the threshold of 20°C. Therefore, it is important to increase either the cut-off wall distance or the thermal insulation thickness. Bearing in mind that the increase in thermal insulation volume might lead to economic infeasibility, it becomes necessary to maintain the thermal insulation thickness and vary the cut-off wall distance.

It is important to mention that the increased thermal insulation quality, even if it does not result in significant improvement in the LTES efficiency, leads to lower GW temperatures compared to the case without insulation ((i.e. U_{side} = 90 W/(m²·K)) and, therefore, it is necessary to provide the required GW protection.

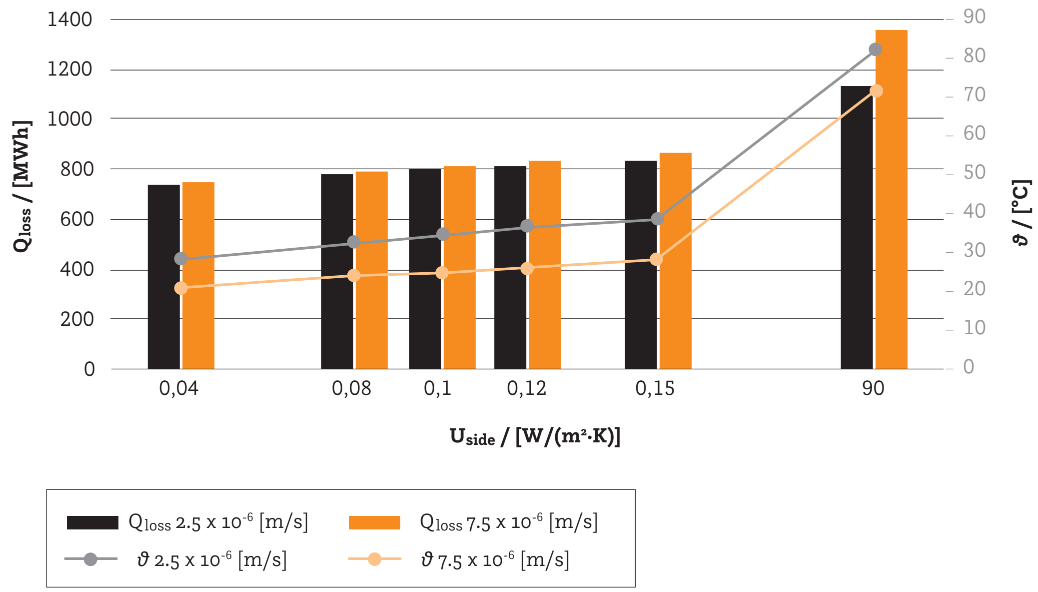


Figure 54: Lateral and bottom thermal losses of an HT 100,000 m³ tank (bar chart, primary left y-axis) and the corresponding downstream temperature on the outer surface of the cut-off wall (line plot, secondary right y-axis) with cut-off wall distance of d_{cw} = 1 m and xins = 1 m (excerpted from [13]).

It is important to highlight the need to investigate in detail the impacts of LTES design and boundary conditions. While the selection of results shown in the previous sections represents a good indication of the possible interactions between LTES and ground, it is necessary to conduct an accurate study using the actual site conditions in the planning phase of an LTES system. The implemented storage level model allows a comprehensive view of the different LTES design factors and ground conditions and constitutes a useful basis for the investigations required in the framework of possible environmental impact assessments.

The results presented in the previous sections show that the transition from favourable geological conditions, with no groundwater, to unfavourable ones, with flowing groundwater, leads to higher thermal losses from the LTES and to ground temperatures exceeding the 20°C limit, violating Austrian groundwater quality management standards. Several effective measures must be introduced to reduce the increase in both the LTES thermal losses and the groundwater temperatures. In this regard, cut-off walls can be introduced together with thermal insulation of the LTES envelope, but these measures must be carefully planned and optimized taking the LTES characteristics into account.

8 Operational and maintenance aspects

During operation it must be ensured that the TES is in adequate condition to store excess energy efficiently and to operate in a way that maximizes the system performance. Thus monitoring, maintenance and control strategy aspects are relevant to guarantee best performance during the long operational phase of the storage. The monitoring aspects are the ones that need to be continuously controlled in order to guarantee and check the correct operation of the storage. However, the maintenance aspects are the ones that need to be carried out regularly in certain intervals to prevent problems or failures. As the control strategy of the storage depends on the role of the storage in the DH system, they are specific to the system and cannot be further addressed in these considerations. During the commissioning and start-up phase material and processing tests guarantee that the construction is properly built, so they will also be addressed in the beginning of this chapter.

8.1 Test in commissioning and start-up phase

Before commissioning, component and processing tests have to be made. The following Table 10 lists essential test and construction steps for state-of-the-art PTES above groundwater level. Aspects of the construction phase like excavation have not been taken into consideration.

Construction phase	**Component**	Liner	Liner	In- and outlets		
	Action / Test	Weld seam tightness test (Figure 55)	Check quality	Check tightness between liner (Figure 56)		
Filling process	**Component**	Pit	Water	Water	Water	Water
	Action / Test	Clean	Preparation via a water treatment system, reverse osmosis	Prevent ice	Prevent organic material and dirt	Check quality of water
Cover process	**Component**	Lid	Thermal insulation	Thermal insulation		
	Action / Test	Removal of water on liner	Prevent from getting humid	Dry if necessary		
Ongoing	**Component**	All components	All components	Groundwater		
	Action / Test	Check accordance with oder/ tender	Take material probes during construction	Check groundwater temperature		

Table 10: Test and construction steps for PTES above groundwater level

Figure 55: Baseliner iss tested for tightness in Høje Taastrup (Source: Gquadrat)

Figure 56: Diffusor connection (left); Laying the liner in Høje Taastrup (Source: Gquadrat) (right)

The following Table 11 lists essential test and construction steps for gigaTES construction types:

Table 11: Construction type tests

Construction phase	**Component**	Cut-off wall	Diaphragm wall	Vertical filter well	Insulation	In- and outlets
	Construction/ Test	• Subsoil probing • Tightness of cut-off wall material, quality control • Tightness of system cut-off wall	Check Quality	• Continuity check • Flow rate test	• CE marking • Quality control	Check tightness liner connection
Cover process	**Component**	Non usable	Fully accessible			
	Construction/ Test	See above	• Individual assembly on the water / • Prefabrication on land	Prevent thermal insulation from getting humid		

8.2 Monitoring

The best way of checking the correct operation of the storage is by monitoring various system parameters with sensors. Measurement and control systems are necessary to promptly detect malfunctions. Monitoring should focus on these three main observations as stated by [16]:

1. Thermodynamic behavior of the TES itself. This includes checking the temperature development in the TES.
2. Interaction of the TES with the system. This should be done by checking the charging and discharging of heat and the yearly energy balance.
3. Interaction of the TES with the surroundings.

Furthermore, the water quality and the construction have to be monitored.
A more detailed overview of monitoring aspects can be found in Appendix E.

Monitor thermodynamic behaviour of the TES itself

Water temperature monitoring

Inside a LTES water temperature must be monitored to see the temperature stratification in the storage. The most common procedure is monitoring the water temperature at different heights of the LTES. Monitoring the stratification is also a matter of ensuring that the storage is utilized in an efficient way and to ensure that the full energy capacity is utilized, the storage can be completely discharged and the maximum temperature for the liner material is not exceeded.

Water level monitoring

The amount of water in the LTES has to be actively monitored, this is done by water level sensors. The lid is moving up and down depending on the water temperature and it is important to calculate where the water surface is expected to be and to control the level of water in order to make sure that no leakages are occurring or do not exceed a certain limit.

Monitor the interaction of the LTES with the system

Water temperature and volume flow monitoring

Temperature sensors at all inlet and outlet pipes are necessary to decide whether the storage can be charged or discharged and at which height of the storage. In order to know how much water and energy is charged and discharged to/from the storage at each inlet and outlet pipe, bidirectional volume flow sensors are installed additionally to the temperature sensors. Installing a heat meter for each pipe is recommended.

Monitor the interaction of the LTES with the surroundings

This includes ground and groundwater temperature monitoring, monitoring heat losses through the lid and wet thermal insulation. For research topics ground temperature can be monitored. For example, this is done at Marstal (Sunstore 4) with five probes with sensors around the storage. Moreover, groundwater needs to be monitored in order to detect heating up beyond a certain critical temperature. Monitoring the temperature of the groundwater around the PTES can also be an appropriate way of detecting leakages, since in the case that leakages occur, the temperature of the groundwater might be increased in that specific region. Heat losses through the lid can be monitored with a heat flux meter. Moisture sensors can be used to detect wet thermal insulation. Visual inspections can also be a possibility for the cover

Monitor water quality

Water quality influences the lifetime and functionality of all parts that are in contact with the storage water. It has been seen that severe contamination of soil particles in the storage can lead to bacterial corrosion of steel parts and clogging of heat exchangers. As a consequence, the water parameters that must be checked include oxygen content, pH value and salt content. Sampling of the water inside the storage system has to be carried out in order to detect anomalies such as corrosion at an early stage. The selection of the materials used determine the requirements for the storage water.

Monitor subsoil and underwater constructions

Checking the construction under the water can be crucial for detecting leakages and corrosion matters. It may be done by diver inspections when the storage is cooled down. An alternative option for a giga_TES is underwater drones which are able to inspect at temperatures up to 80 °C. An electric leak detection survey of the exposed geomembrane area may also be possible. See Figure 57

Figure 57: Leakage detection system for PTES in Høje Taastrup (Source: Gquadrat)

Cover inspections

The two main cover related problems that exist with state-of-the-art PTES are air underneath the cover and risk of puddles of water forming on the lid. Due to the huge surface the cover of a Giga-scale TES would have, possibilities like using drones for visual inspections need to be taken into account.

Maintenance

The monitoring aspects mentioned before have to be done regularly in different intervals. If monitoring detects any malfunction or damage of the storage, reparation or maintenance is done. Nevertheless, some parts of the storage should be maintained regularly. They include: cleaning the filters throughout storage cycles and in vertical well.

9 Conclusions and outlook

Within the gigaTES project developments on concept level, on material level, on component level and on system level have delivered a number of very valuable results and represent a step forward in implementing large thermal energy storage (LTES) for renewable district heating systems. On materials development level, a novel polymer liner was developed, and dedicated tests showed that we can expect a doubling of lifetime under higher temperature conditions compared to existing liner materials. On component level, i.e., cover and wall constructions new concepts were developed, numerical investigations and laboratory tests were performed and real scale-mock-ups were built and tested.

Building an LTES with high efficiency in an urban environment, with minimal impact on the groundwater temperature, requires more sophisticated building technology than for the TES currently being realized e.g. in Denmark. gigaTES was successful in generating a number of building concepts that keep within these boundary conditions. A new patented method to add a thermally insulating underground ring around the storage was devised and tested on mock-up scale. As for the very important cover, that due to the required combination of thermal insulation, water tightness, water vapour tightness as well as load bearing capability, constitutes the most expensive component, two new, patented concepts were developed that enable additional use of the storage cover where land is expensive.

The planning, design and building of a large thermal energy storage is restricted by a large number of boundary conditions. These conditions were gathered and together with the aspects that should be taken into account when commissioning and operating the storage, form a very practical guideline for those thinking about the realisation of a large thermal storage in a district heating system.

Key for implementing LTES is thorough planning and design. Thus, the project developed a series of numerical simulation tools that enabled to optimise the functioning of the LTES within the given environment, for instance, in presence of ground water, and the integration of the storage in renewable district heating systems. LTES design has to be optimised depending on its interaction with the surrounding soil and with the groundwater flow. The influence of different concepts for thermal insulation, either inside or outside the storage wall, the thermodynamic behaviour of the water in the storage and thus the storage energetic and exergetic efficiency as well as the interaction with surrounding ground water was investigated by means of detailed multi-annual simulations. System simulation show the optimal integration of the TES in the district heat system and its dynamic behaviour.

The modelling of the system performance of the storage was combined with a building cost tool, that holds the costs of all components, materials and building processes taken from present deep construction experience, to enable a cost optimisation of the large thermal energy storage in a given district heating constellation. There were two case studies taken for a complete cost calculation and the resulting levelized cost of storage were already on a good level but not as low as the presently existing large storages. This is understandable, as the requirements to the storage in Central-European conditions are relatively high.

The target of the gigaTES project was to enable the demonstration of a large thermal energy storage for district heating in Austria. This aim was achieved. We have developed sufficient knowledge to plan, design and test this LTES. The challenge is to find an optimum between the risks of a demonstration and the cost of a large thermal energy storage. The demonstration would need to give answers to questions that were generated in the project: what are the best and most cost-effective construction methods for the designed gigaTES concepts? What is the long-term mechanical behaviour of a gigaTES storage in the underground? What are the best construction methods for insulation and liners? How do the newly developed materials behave in practice? These questions are best addressed in smaller demonstration projects to start with. With these, valuable practical experience will also be gained that will help to drive down the risks and costs of consecutive generations of larger thermal energy storages.

Also internationally, the gigaTES project has set a new mark for the development of LTES. Plans are being developed in a number of countries, for instance Denmark, Germany, The Netherlands, Serbia, Kosovo and Poland, and the developments would definitely benefit from and being accelerated by a concerted European collaboration. Moreover, the higher European goals for CO_2 emissions reduction have increased the necessity for a swift introduction of LTES, also in large systems. Therefore, the outlook is that the coming years will see a number of novel demonstration projects, novel concepts and integrations methods and novel tools and equipment for LTES.

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11 Appendices

Appendix A: LTES loading profiles – Case study A and B

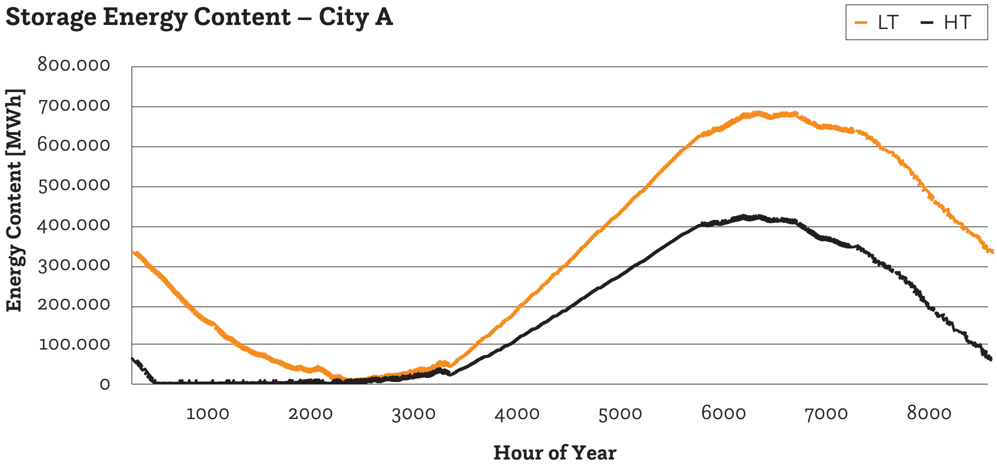

Figure 58 Storage Energy Content for LT and HT variants in Case Study: City A (1,200,000m³)

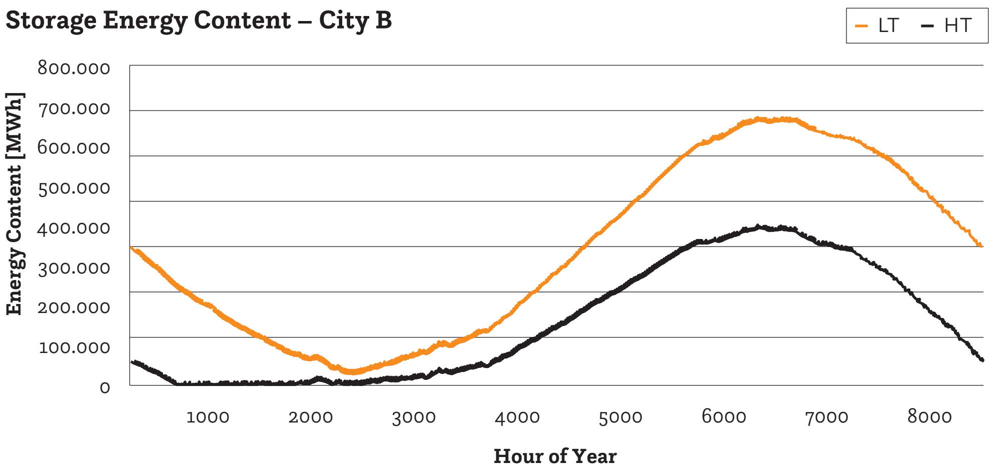

Figure 59: Storage Energy Content for LT and HT variants in Case Study: City B (100,000m³)

Appendix B: CO_2 emission factors

Emissions factors	tCO_2/GWh_{th}
Gas	244
Biomass	50
Waste Heat	22
Solar	0
Geothermal	0

Appendix C: Levelised Cost of Storage (LCOS) Evaluation

The LCOS calculation used for the case studies uses the annuity method, which estimates a fixed annual payment every year over the lifetime of the storage and is expressed as follows:

$$LCOS = \frac{CAPEX_{yearly,LTES+periphery} + OPEX_{yearly}}{E_{discharged,yearly}}$$

The yearly CAPEX values are calculated based on the total CAPEX multiplied by a given annuity factor. The annuity factor is expressed as follows:

$$Annuity,f = \frac{(1+r)^n}{r}$$

Where r is the given interest rate in % over the payback period and n is the number of years for the expected payback period.

For both use cases, the interest rate r was assumed to be 4%.
The lifetime of the storage, n, was assumed to be limited to the lifetime of the liner.
The CAPEX includes the investment cost of the LTES itself as well as any basic peripheral equipment such as heat exchangers, pipeline and pumps. The assumption was that the LTES is located relatively close to the DH network so pipeline costs are kept to a minimum. Water sourcing and treatment for filling the LTES are also included in the peripheral system costs at a total cost of €2.5/m3 of water.

The OPEX costs were taken to be €1.3/MWh of storage capacity per year (Deliverable 3.3 – HeatStore) + 1% of the peripheral system CAPEX per year – the estimates here are very rough due to the fact that no such storage of this scale or design are yet in operation and are simply extrapolated values from existing storages (In the case of the 1,200,000m3 storage).

The cost of heat used to charge the storage is not included in the LCOS calculations.

Appendix D: Boundary conditions for LTES

Category				Boundary Condition		Unit	Description
I Location	A	Geological and hydrogeological	Geology Hydrogeology	A1	geological model	model	defining different lithological units (= type of rock), their extent and homogenity and their essential geotechnical parameters
				A2	hydrogeological model	model	hydrogeological properties of different lithological units (e.g. thickness, permeability, porosity, thermal conductivity, specific heat capacity etc.) of Overlay, Aquifer and Aquiclude
			General groundwater conditions	A3	number of aquifers	number	
				A4	confined / unconfined	c/u	the groundwater is under pressure or not
				A5	groundwater level	m	mean, min, max, including extremes, distance surface to groundwater level
				A6	flow direction and gradient of groundwater		
				A7	temperature of groundwater	°C	actual temperature of the groundwater
				A8	chemism of groundwater		
				A9	existing contamination	Yes / No	(geogene/anthropogene)
			Misancellous hydrogeo-logical parameters	A10	infiltration in vicinity (possible ?)		
				A11	risk to raise the groundwater table	High/ Medium/ Low	Is there a risk to raise the groudwater because of "damming effects"
				A12	risk to lower the groundwater table downstream of the storage	High/ Medium/ Low	Is there a risk to lower the groundwater table downstream of the storage?
				A13	seepage of storage water		Is there risk of contamination?
	B	Site	Other location based conditions	B1	existing contamination	Yes / No	Is there geogene or anthropogene condamination?
				B2	reuse of existing structures	Yes / No	Is there a possibility to use existing structures?
				B3	costs of land	Euro/m²	What are the costs for a m² land?
				B4	near located disposal site	Yes / No	Is there a near located disposal site for excavation?
	C	Environmental conditions	"Climate"	C1	precipitation	mm/a (l/(s*km2))	in the course of the year
				C2	evapotransporation	mm/a (l/(s*km2))	in the course of the year
				C3	groundwater recharge	mm/a (l/(s*km2))	in the course of the year
				C5	outside Temperature	°C	in the course of the year
				C6	relative humidity	%	in the course of the year
				C7	wind velocity	m/s	in the course of the year
				C8	solar radiation	W/m²	in the course of the year

I Location	C	Environmental conditions	Natural hazards	C9	seismicity	High/ Medium/ Low	Is there a risk for earthquakes
				C10	high water, flood risk	High/ Medium/ Low	HQ30, HQ100
				C11	landslide and avalanche risk	High/ Medium/ Low	Is there a risk for landslides and avalanches?
				C12	risk of high groundwater	High/ Medium/ Low	Is there a risk for high groundwater?
				C13	risk of mass movement	High/ Medium/ Low	Is there a risk for mass movement?
II Material	D	Properties of materials	Properties of liner	D1	max. temperature of liner	°C	the maximum temperature the liner can resist without shortening life expectancy
				D2	other limitations of liner		
				D3	lifetime of liner	years	lifetime in regard to max. temp.
				D4	dimensions of liner	m	possible lenght, width and thickness
				D5	diffusion resistance factor of liner	-	hygrothermal properties of liners
				D6	corrosion resistance of liner	High / medium / low	case of metal-based liner & if interacting with the groundwater
			Properties of concrete	D7	thermal conductivity of concrete	W/mK	hygrothermal properties of concrete
				D8	diffusion resistance factor of concrete		hygrothermal properties of concrete
				D9	moisture retention curve of concrete		hygrothermal properties of concrete
				D10	liquid water diffusivity of concrete	m^2/s	hygrothermal properties of concrete
				D11	lifetime of concrete	years	lifetime in regard to max. temp.
				D12	cover liner construction		
				D13	Thermal insulation of the material		
III DH System	E	DH characteristics & Integration into DH grid	Properties of DH-network	E1	DH grid structure, No. of customers etc.		different temperature levels, primary/secondary networks
				E2	max. system pressure	bar	pressure can be variable, little relevance-cost
				E3	capacity of transport and distribution pipes	DN, material, insulation, max. capacity, total pipe	of the network, but mainly important at integration point
				E4	topology	linear, circular, mesh, ..	

	E5	heat density [3]	heat map, MWh/ km^2.y	How dispersed is the heat demand in the network? Only relevant for future extansions plans
Properties of supply / consumption	E6	temperature profile in Winter / Summer / transition period (supply and return)	°C	temperatures of the DH-system in the course of a year
	E7	summer and winter load duration curves	MW	load of the DH-system in the course of a year
	E8	current heat source	CHP, Gas boiler, biomass, ...	What heat sources are used in the DH-system?
	E9	current (peak) heat demand / yearly overall demand	MW, MWh	peaks in DH-demand and yearly overall demand
	E10	flexibility / redundancy plans		mainly dependend on energyeconomics-max heat power for peaks in MW. also N-1 security important here TES is flexible because it can serve both as source and sink - business models would have to be considered
	E11	supply reliability		ratio max nominal load/capacity installed, back up pumps
Costs	E12	current heat production costs	Euro/ MWh	
	E13	current heat sale prices	Euro/ MWh	actual heat sale prices
Potentials and strategies	E14	pot. capacity for storing heat	MWh/y	What is the available amount of thermal energy in the DH-system that has to be stored?
	E17	future extension / decarbonizazion plans?	plan	What are future plans of the DH-system operator?
	E18	current unit commitment / dispatch strategy		
Storage integration	E19	distance to DH network	m	how far away are the storage from the DH-network
	E20	obstacles on connection line	motorways, rivers, train tracks, mountains	Are there obstacles on the connection line?
	E21	height differences between storage and DH grid	m	What is the high difference between the grid and teh storage?
	E22	additional heat sources etc. nearby?		Are there additional heat sources near the connection point?
	E23	temperature levels at connetion point	°C	
		capacity of the network at integration point	MWh	How much energy can be fed into the network?

IV Authorities	F	Regional & spatial planning / land availability		F1	water conservation / preserve area	Yes/No (Yes with restrictions)	
				F2	nature reserve	Yes/No (Yes with restrictions)	
				F3	flood control/risk zone	Yes/No (Yes with restrictions)	
				F4	recreation area	Yes/No (Yes with restrictions)	
				F5	industrial zone (in future)	Yes/No (Yes with restrictions)	
				F6	ecological & protective zone	Yes/No (Yes with restrictions)	
				F8	distance to road network	m	closer to existing infrastructure, better
				F9	energy master plan	increase/ decrease DHN penetration, …	What is the energy master plan of the region?
				F10	land use & planning		dedication
				F11	ownership structure		is the land divided by more owners
	G	Legal requirements & public permissioning		G1	construction and building law		legal aspects will have a big impact on costs, including construction / development time Research of the current status quo: Ö / DK / D & BSG experiences
				G2	environmental impact assessment (UVP-G)		includes Visual and Landscape impact assessment
				G3	foreign laws		water protection area; wells for drinking water and other applications; geothermal ground probe; other applications with rights which use the ground or groundwater in the surrounding area (water water heat pumps, cooling….);
				G4	existing water rights		

Appendix E: Monitoring aspects[1]

Aspect	Method	Goal	Interval	Compulsory/beneficial
Water temperature	Vertical strings/ piles with temperature sensors at different heights	Calculate the energy content of the storage. Be aware of spoiled stratification Be aware of temperature load on liners [1]	1-10 min	Compulsory
Ground temperature	Vertical probe with temperature sensors at different heights and within different distances to the TES for legislation only one sensor is compulsory	Mainly for research in some cases may be relevant for legislation. Leakage detection.	10 to 60 min [1]	Compulsory/Beneficial
Water level	Water level sensors, **ultrasonic or capacitive level sensors, (guided) wave radar, hydrostatic pressure**	Know filling percentage Comment: Depending on the existence of overflow and compensation reservoirs [3]	10 to 60 min [1]	Compulsory
In- and outlet pipes flows	Volume flow sensors	Calculate the expected heat flow	1-10 min	Compulsory
In- and outlet pipes temperatures	Temperature sensors	Control strategy and heat power [2]	1-10 min	Compulsory
Cover heat losses	heat flux meter	Calculate the cover heat losses and the storage efficiency	10 to 60 min [1]	Beneficial
Cover moisture	Moisture sensor in the cover	Detect wet insulation	10 to 60 min [1]	Beneficial
Rain	Rain sensor or visual supervision [2]	Detect the risk of water ponds on the cover	10 to 60 min [1]	Beneficial
Check cover	Visual supervision	Detect possible issues?	At least once a week,	Compulsory / Beneficial
Check construction	Divers, underwater drones	Detect possible issues	If necessary	Beneficial
Check acidity of the water in the TES	Sampling	Prevent corrosion	At least once a year (depending on water amount)	Compulsory / Beneficial
	Sampling	Expand lifetime of the liner etc.	Will be checked continuously in Høje Taastrup [2]	Beneficial
Check bio residuals content	Sampling	Ensure appropriate content	Once a year	Beneficial
Check other ingredients in the TES water [1]	check iron content (corrosion issue), conductivity sensor (indicates saline condition)	Ensure appropiate content	continuously or once a month	Beneficial
Control water delivery rate of vertical well	Volume flow sensors	Check if well is working well	continuously	Beneficial

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