Investigation of the Role and Design of Thermal Insulation in the Envelope of Buried Large-Scale Thermal Energy Storage

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Abstract

In an urban context, the size of large thermal energy storage (LTES) is limited by space availability and by high land costs, so deep LTES systems with insulated vertical walls are a promising alternative to the state-of-the-art shallow pit TES. The design of buried LTES envelope is investigated using a finite-element (FE) based numerical model. The focus is a detailed thermophysical representation of its envelope with thermal insulation. This geometric representation allows to investigate the envelope design and its influence on LTES performance as well as on the surrounding ground temperature. Additionally, the influence of the envelope modelling approach (i.e., detailed geometric/thermophysical vs. resistive) is investigated. Purely resistive models are sensitive to insulation quality, but are not able to model the effects of insulation location or 2D heat flux. For the same insulation quality, cases with external insulation show lower performance than cases with internal insulation. In particular, the energy efficiency is about 2% lower and the exergy efficiency is 5% lower with external insulation than with internal insulation.

Keywords: large-scale thermal energy storage, envelope, numerical modelling, thermal insulation, energy, exergy

1. Introduction

The shift to an energy system based on fluctuating renewable energy (RE) sources requires the implementation of additional storage solutions to decouple the energy supply and demand and to increase the resilience and robustness of the system (Lyden et al., 2022). In the building stock an additional challenge is the seasonal mismatch between the energy demand of the buildings (in winter primarily driven by space heating) and the availability of energy sources like solar energy. Water-based large-scale thermal energy storage (LTES) have been successfully introduced in several district heating (DH) systems to increase the RE share and cover this seasonal mismatch (Dahash et al., 2019).

1.1. TES construction solutions

The construction solution of a LTES system is often underground due the large storage volumes required, which conflict with space availability -especially in urban areas- and social acceptance (Sträter et al., 2025). Restricting the analysis on water-based storage solutions, the two construction strategies available are the shallow pit TES (PTES), and the tank TES (TTES). The PTES solution minimizes earthworks by shaping the soil into sloped walls (30°-40°) thus avoiding expensive geotechnical structures (Ochs, 2009). However, this results in wide LTES with a low aspect ratio (height-to-diameter ratio), which is unfavorable both in terms of space and thermodynamic performance. In fact, the LTES performance is affected by the thermal losses towards the surroundings and by the internal temperature losses due to the decay of thermal stratification (Sifnaios et al., 2022). Cylindrical or hybrid structures like TTES offer a more compact shape that allows to maintain a better thermal stratification, but their costs per unit volume are significantly higher (Schmidt et al., 2018). The steeper walls in existing TTES systems have prefabricated concrete elements (e.g., Munich Ackermannbogen) or steel structure (e.g., Berlin). In buried TTES systems the vertical walls can be constructed using the diaphragm wall (DW) method, but the production accuracy limits the depth to approximately 50 m (van Helden et al., 2021).

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In order to reduce the thermal losses and minimize the thermal stratification decay, thermal insulation is recommended especially in the envelope elements in contact with upper TES layers, where the average temperature over the year is higher. The cover of buried LTES systems (both TTES and PTES) is always insulated, while the insulation of lateral walls is not always economically convenient due to the high costs of installation especially in the tilted walls of PTES (Bott et al., 2019). Existing PTES do not generally present lateral wall insulation, while sidewalls of TTES are usually insulated especially in case of partially buried solutions (e.g., Munich TTES (Mangold & Deschaintre, 2015)). In TTES systems, the thermal insulation can be installed within the concrete structure (internal insulation) or on the external side (external insulation) (Ochs, 2009). The advantage of internal insulation is a lower temperature-induced stress on the concrete layer, but it presents a difficult realization during the construction. Moreover, in presence of moisture (due to leakage, diffusion, infiltration or from construction) ensuring the drying of the material is necessary and proper ventilation solutions to remove the trapped moisture should be considered (Bott et al., 2019). External insulation presents the advantage of easier installation and maintenance, but materials with good structural stability are required to resist against ground pressure. The LTES bottom is usually not insulated, as the lower water layers present a lower average temperature, resulting in lower thermal losses.

Larger volumes can compensate for the lack of sidewalls insulation in the LTES efficiency evaluation thanks to the larger capacity (Ochs et al., 2020). However, this may not be a feasible solution in the presence of shallow groundwater (GW), which increases the LTES thermal losses due the advective losses driven by the GW flow, which in turn increases the downstream GW temperature (Bott et al., 2024). Depending on local regulations, permission to build and operate a LTES is conditional upon maintaining surrounding soil temperatures within specific limits (Blum et al., 2021). The installation of thermal insulation and the use of cut-off walls (i.e. barriers with very low permeability), usually employed to stop the migration of pollutants to the GW or to reduce seepage through dams, are necessary measures to prevent GW overheating (Dahash et al., 2021).

1.2. Modelling approaches of LTES envelope

Modelling LTES systems is fundamental to supporting the design process. Dahash et al. (2019) propose a hierarchy for the LTES modelling process based on the various planning stages, ranging from preliminary design to specific construction optimisation. The element in common between all these phases is the possibility to include the TES operation, albeit with different degrees of detail in terms of LTES geometry, interaction with the surrounding environment and energy system components and envelope.

Rather than following a one-directional modelling path, from a ‘very simple’ model (1D TES domain without ground) to a ‘very detailed’ model (3D TES with GW flow and detailed envelope) to support the design phase, an approach is suggested that is directed at tackling the specific problems of planners. A simplified scheme is presented in Figure 1. This distinction is based on specific engineering (e.g., GW permeation, materials selection) and physical (e.g., insulation degradation, exergy loss) problems affecting the operation of a buried LTES. These two domains are not necessarily distinct, but respond to different requirements and design stages.

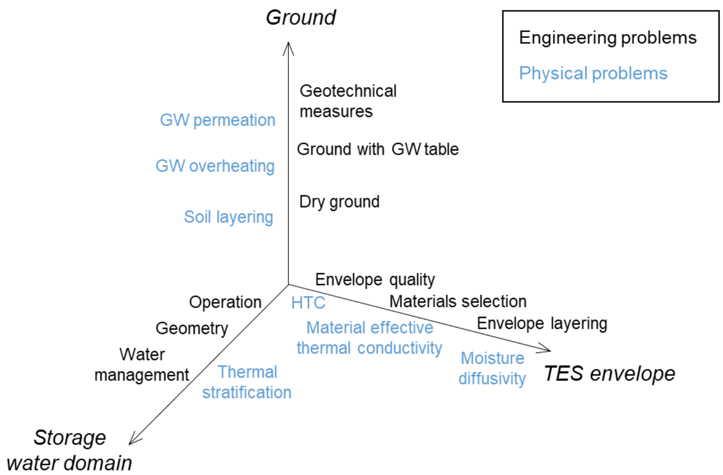

Figure 1: Modelling elements of LTES systems for the three elements of storage, envelope and ground.

For the detailed numerical modelling of LTES systems several tools are available (Schmidt, Dahash, et al., 2024), but a major distinction can be found between finite elements (FE)-based tools and finite difference (FD)-based tools (Tosatto & Ochs, 2024). Both these approaches allow to model the LTES geometry (i.e., lateral wall slope), with consistent and comparable results concerning the LTES performance in terms of thermal stratification and energy balance when a simplified (resistive-R) approach for the envelope is considered (Schmidt, Reisenbichler-S., et al., 2024; Tosatto & Ochs, 2024). However, the FE approach offers significant advantages in the detailed geometrical modelling of the LTES envelope in presence of slopes and irregularities, whose single layers can be directly modelled considering their thermal properties, and a more refined mesh for these domains can be manually defined. This level of detail allows to account for specific design solutions (e.g., internal vs. external insulation, insulation quality) which cannot be considered with a resistive approach, and to investigate the 2D heat transfer within the single envelope elements.

A further advantage of FE models is the possibility to include multiphysical aspects, such as the GW flow (Dahash et al., 2021) and the moisture transport within the materials, thus allowing to bring the LTES modelling from a system level to a detailed component level. This additional level of complexity however introduces significantly higher computational efforts, related to the increased mesh refinement to ensure a good modelling accuracy and the additional equations that need to be solved.

1.3. Research question

A research gap has been identified in understanding how the geometrical characteristics of the LTES envelope affect its performance. The sidewalls insulation location (internal vs. external), vertical extension and quality affect the thermal losses distribution and hence the LTES performance and the surrounding ground temperature. Material discontinuities and geometrical irregularities can lead to the formation of thermal bridges (e.g., at the intersection of the cover and lateral walls) and 2D heat flux phenomena in the lateral envelope, resulting in higher localized thermal losses and affecting on the local hygrothermal conditions. Due to the high cost of thermal insulation in terms of materials and installation, it is necessary to understand and quantify these effects in order to optimise the design from a techno-economic perspective.

This work investigates the influence of different wall constructions (varying in insulation depth, quality and thickness) on storage efficiency and on surrounding ground temperatures, using a FE-based numerical LTES model with a detailed thermophysical (TP) representation of its envelope.

2. Methods

A numerical model of a buried cylindrical LTES with coupled solid and fluid domain is built in COMSOL Multiphysics. In absence of GW flow, the TES and surrounding ground can be simplified with an axisymmetric model. The fluid domain is modelled as a 1D line source with a FE discretization in n-vertical layers as from Eq. 1, where the buoyancy effects are considered in the effective water thermal conductivity as presented in more detail by (Tosatto & Ochs, 2024). The thermal losses term (Eq. 2) couples the LTES water domain and the solid domain. The envelope and the ground surrounding the LTES are modelled in 2D as a solid domain, according to Eq. 3, where *m* defines the solid domain of insulation or solid ground.

$$\rho A_i c_p \frac{dT_i}{dt} = \rho \dot{V} c_p \nabla T_i + A_i \nabla \cdot \left(\lambda_{eff,mix} \nabla T\right) - \dot{q}_{loss,\,i} \quad \text{(eq. 1)}$$

$$\dot{q}_{loss,\,i} = h_{conv}(T_i - T_{m,i}) \quad \text{(eq. 2)}$$

$$\rho_m c_{p,m} \frac{\partial T_m}{\partial t} = \nabla \cdot (\lambda_m \nabla T_m) + \dot{q} \quad \text{(eq. 3)}$$

In Table 1 the parameters used to model the water in the LTES and the solid ground are presented.

Table 1: Thermophysical properties of the water in the LTES and of the surrounding soil used in the simulations.

	k / [W/(m·K)]	ρ / [kg/m^3]	c_p / [J/(kg·K)]
Water	0.66	975	4192
Unsaturated soil	2	1750	800

Figure 2 presents the two insulation solutions (external vs. internal) modelled in the FE tool. Although the GW flow and cut-off walls are not modeled in this analysis, they are included in the figures for completeness and to provide context regarding the system layout. The storage is charged at 95 °C and discharged at 42 °C, while the initial ground temperature and the surrounding air are assumed to be constant at 10 °C.

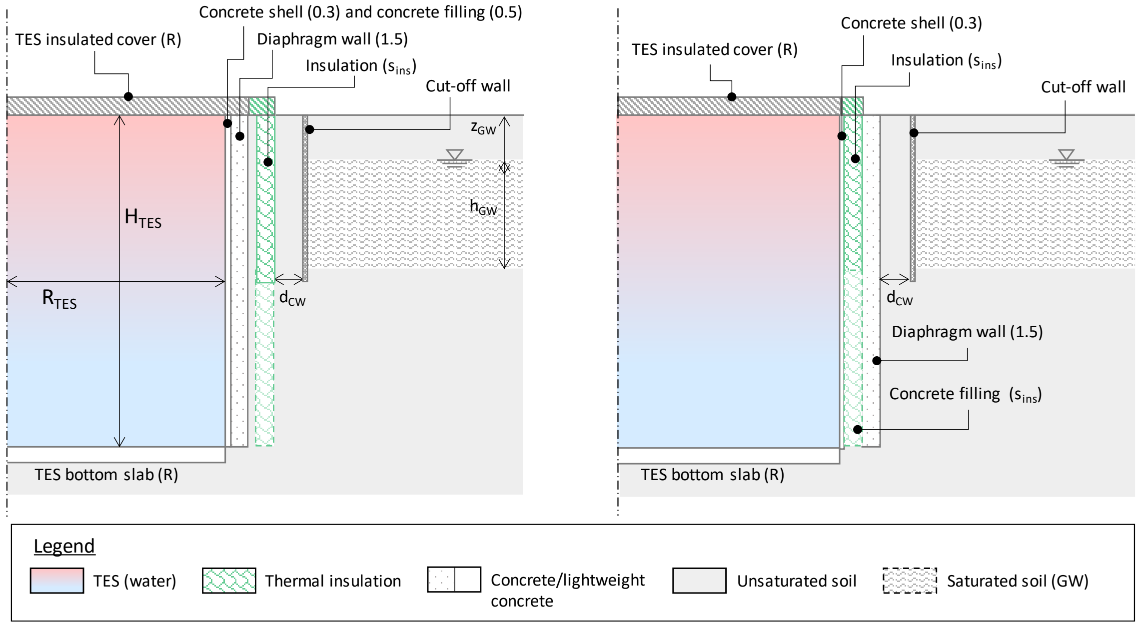

Figure 2: Axisymmetric representation of the investigated buried LTES (40 500 m^3) with external insulation (left) and internal insulation (right). Numbers in parentheses indicate the thickness of each layer (in [m]). Cover and bottom slab are modelled as thermal resistances (R). Note: figures are not to scale.

Two different storage sizes are also considered to account for the role of storage capacity on the final performance of the LTES: the smaller LTES has a diameter of 42 m, and a height of 30 m, for a total volume of 40 500 m^3 and a capacity of 2.5 GWh, the larger one has a diameter of 150 m and a height of 40 m for a total volume of 706 800 m^3 and a capacity of 43 GWh.

2.1. LTES envelope models

The LTES cover and bottom are modelled as resistances, with heat transfer coefficients (HTC) of 0.1 W/(m^2·K) and 1.5 W/(m^2·K) respectively. The diaphragm wall is assumed to be made of concrete (C) and different variants for the concrete filling are investigated (concrete C and lightweight concrete LC). The material properties are presented in Table 2.

The following envelope variants are studied for the two LTES sizes:

- Lateral insulation location: internal (int), external (ext), as presented in Figure 1.
- Modelling approach: thermophysical envelope (TP) and resistive envelope (R).
- Insulation depth with respect to the LTES height: 50 % (only upper half), 75 % and 100 %.
- Insulation thickness (s_{ins}=[0. 5 1 1.5] m) and thermal conductivity (k_{ins}=[0.05 0.1 0.15] W/(m·K)).

Table 2: Thermophysical properties of the envelope materials.

Envelope material	**k / [W/(m·K)]**	**ρ / [kg/m^3]**	**c_p / [J/(kg·K)]**
Concrete (C)	2.3	2300	1000
Insulation	0.05 0.1 0.15	200	1000
Lightweight concrete (LC)	0.3	1000	1000
	HTC / [W(m^2·K)]		
HTC water/ TES wall (h_{conv})	100		
TES cover	0.1		
TES bottom slab	1.5		

This range of thermal conductivity has been chosen considering the insulation materials commonly used for the insulation of existing LTES systems (Ochs, 2009): 0.05 W/(m·K) corresponds to the mineral wool and 0.15 W/(m·K) to foam glass gravel in presence of degradation phenomena like natural convection and moisture. The HTCs of the lateral walls used in the corresponding resistive (R) models are presented in Table 3.

Table 3: HTC of the lateral TES wall for the investigated insulation combinations, with external insulation (left) and internal insulation (right).

overall HTC / [W/(m²·K)]	k_{ins} / [W/(m·K)]				k_{ins} / [W/(m·K)]		
s_{ins} / [m]	0.15	0.1	0.05		0.15	0.1	0.05
0.5	0.214	0.158	0.088		0.242	0.173	0.093
1	0.125	**0.088**	0.047		0.134	**0.093**	0.048
1.5	0.088	0.061	0.032		0.093	0.063	0.032
uninsulated wall section	0.3 (LC filling) – 0.54 (C filling)				0.27 (LC filling) – 0.8 (C filling)		

A seasonal operation of the LTES is investigated, with a charging/ discharging profile derived from the TES volume according to the indications from (Schmidt, Dahash, et al., 2024). An operation period of 10 years is simulated. A short-term operation is also investigated.

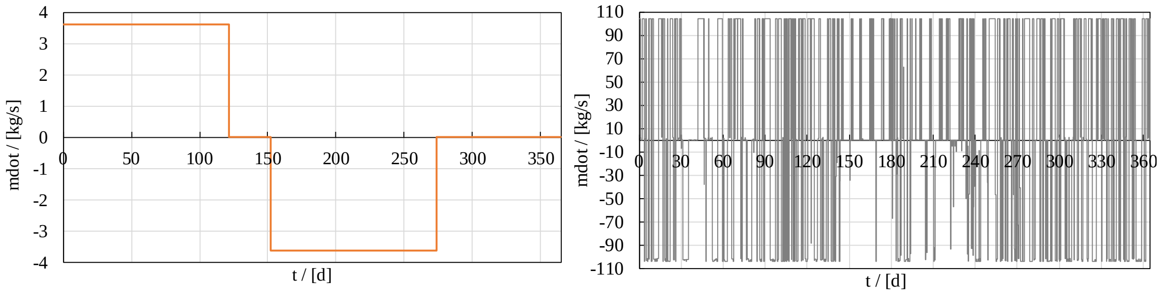

Figure 3: TES operation: input/output volumetric flow. Seasonal operation (left), short term/weekly operation (right).

2.2. Key Performance Indicators

The following key performance indicators (KPIs) are used to compare the different TES envelope variants, and are presented in Equations 4 to 7: TES energy efficiency, TES discharge temperature, TES exergy efficiency. These allow to assess the LTES performance at a component level. In order to consider the effect on the surrounding ground and GW, the soil temperature at the external side of the cut-off wall is considered.

$$\eta = 1 - \frac{Q_{loss}}{E_{TES,max}} \quad \text{(eq. 4)}$$

$$\psi = \frac{EX_{dis}}{EX_{ch}} \quad \text{(eq. 5)}$$

$$EX_{ch} = \int \rho\, c_p\, \dot{V}_{ch} \left[(T_{ch} - T_{out}) - T_0 \ln\left(\frac{T_{ch}}{T_{out}}\right) \right] dt \quad \text{(eq. 6)}$$

$$EX_{dis} = \int \rho\, c_p\, \dot{V}_{dis} \left[(T_{out} - T_{dis}) - T_0 \ln\left(\frac{T_{out}}{T_{dis}}\right) \right] dt \quad \text{(eq. 7)}$$

3. Results

3.1 LTES envelope models

In this section the influence of the envelope model and structure is considered for the mid-size LTES in seasonal operation mode. The seasonal operation (see Figure 3) includes two idle phases, which allow to investigate the effect of the envelope capacity on the LTES operation. The LTES with a volume of 40 500 m³ is considered in this first analysis as the performance of lower capacities is more affected by the envelope quality, due to the larger area-to-volume ratio compared to larger LTES (Ochs et al., 2020).

In order to gain an indication on the LTES performance for all the investigated cases, the energy and exergy efficiencies for the 10th year of operation are derived using Eq. 6 and 7, and are presented in Figure 4. The graphs show the efficiencies derived for all the investigated models with respect to the reference model, which has been chosen to be the ‘R int ins LC’. This representation allows to distinguish the effect of envelope model from the effect of construction quality.

The LTES efficiency (left figure) varies between 0.85 and 0.92 depending on the insulation quality (x-axis range) and between 0.83 and 0.85 and 0.9 and 0.92 depending on the envelope model (y-axis range). The LTES exergy efficiency (right figure) varies between 0.75 and 0.88 depending on the insulation quality and between 0.75 and 0.8 and 0.83 and 0.88 depending on the envelope model. It is possible to see for both indicators that the points corresponding to the ‘R ext ins C’ case are almost all comparable to the reference model ‘R int ins LC’, as none of these two approaches is able to account for the insulation thickness and location with respect to the DW, with the only minor difference being related to the quality concrete filling. Generally, the internal insulation solution outperforms the external insulation.

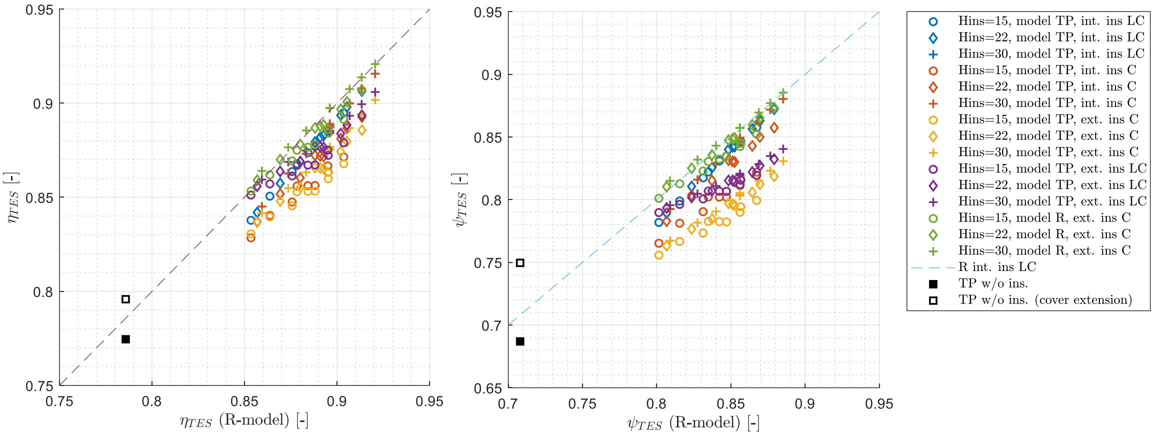

Figure 4: TES energy efficiency (left) and exergy efficiency (right). The different colors represent the envelope model approach (TP vs. R), insulation location (int. vs. ext.) and type of concrete filling (C vs. LC), while the symbols distinguish the insulation depth over the LTES height. The efficiency values for the different models are reported against the corresponding efficiencies obtained with a resistive model with the same insulation quality.

The exergy efficiency accounts for the energy quality and therefore for the degradation of the thermal stratification within the water domain, driven by the thermal losses, hence its values are lower than the energy efficiency values. The top LTES water temperature is a direct indicator of this thermal decay and some relevant cases with the same insulation quality (i.e, thermal conductivity and thickness) are presented in Figure 5 for the last year of operation investigated in the simulations. The most relevant period (highlighted in the zoom box) is the discharge phase, as the outlet temperature directly affects the effective energy available for the DH grid and the need for eventual post-heater. Also, this KPI shows a higher performance for the ‘TP, int ins’ case, comparable to the R-models. A deeper extension of thermal insulation (50 % in the left figure and 100 % of the LTES height in the right figure) limits temperature loss at the end of the discharge phase, but with minimal advantages for the ‘TP, ext ins’ cases.

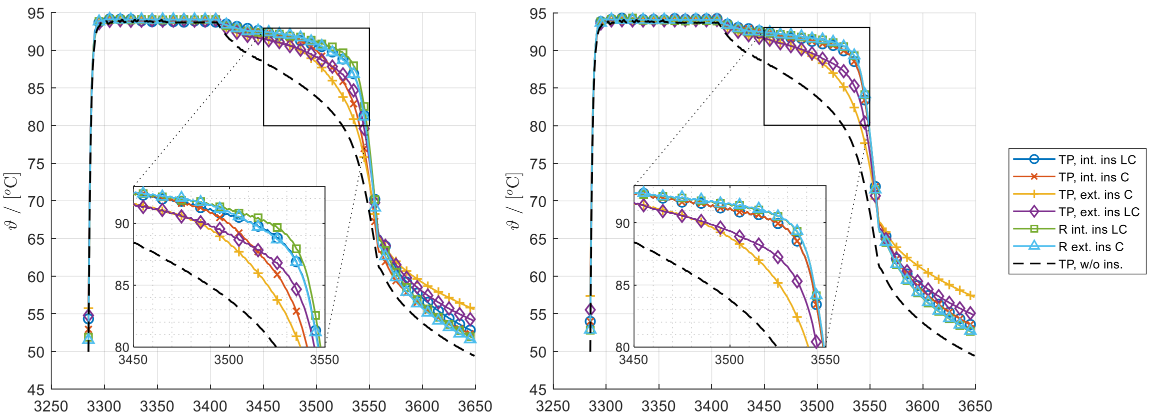

Figure 5: LTES output temperature in absence of GW for the investigated LTES with insulation quality k_{ins}= 0.1 W/(m·K) and s_{ins}=1 m and depth up to 50 % of the LTES height (left) and 100 % of the LTES height (right).

The different performance for the investigated cases is related to the thermal losses towards the ground. Table 4 shows the LTES total thermal losses for the same cases presented in Figure 5.

Table 4: TES total thermal losses (MWh/a) the 10th year of operation for the 40 500 m³ LTES (seasonal operation) with insulation quality k_{ins}=0.1 W/(m·K) and s_{ins}=1 m.

	Insulation depth (% of TES height)		
	50 %	**75 %**	**100 %**
TP int. ins. LC	316	295	280
TP int. ins. C	360	320	280
TP ext. ins. LC	332	308	288
TP ext. ins. C	367	336	310
R int. ins. LC	290	273	260
R ext. ins. C	309	281	257
w/o ins	454 – 404 (with cover extension)		

The higher losses in the 'TP ext ins' cases are related to the 2D heat transfer effects in the concrete diaphragm wall. These effects are better highlighted by the 2D representation of the temperature distribution in the LTES envelope and ground presented in Figure 6. The external insulation and internal insulation cases with insulation quality 0.9 W/(m²·K) are presented. The timeframe chosen is the end of the storage phase, when the ground temperature is higher. The 2D heat transfer effect is visible from the black arrows showing the heat flux pattern, while the coloured lines represent the thermal isotherms. Despite closer values for the overall HTC of the LTES envelope, the higher thermal losses in the external insulation case result in higher ground temperatures.

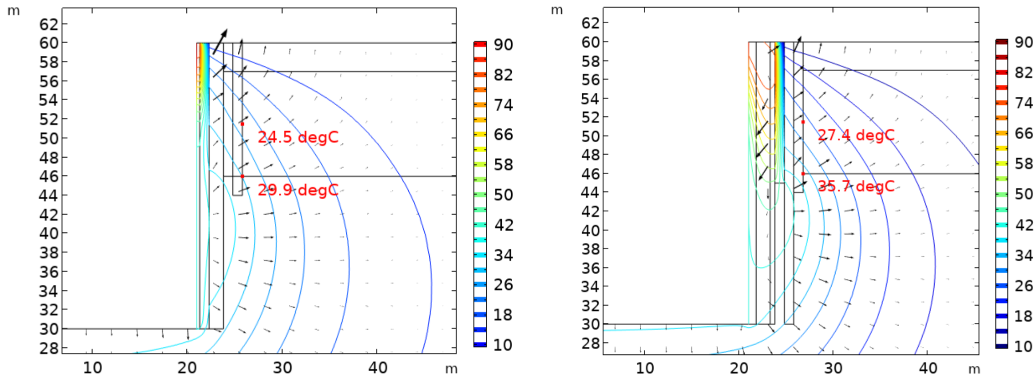

Figure 6: Temperature distribution in the LTES envelope and in the ground in absence of GW for the investigated LTES with insulation quality k_{ins}= 0.1 W/(m·K), s_{ins}= 1 m, H_{ins}=15 m (50 %), case with internal (left) and external insulation (right).

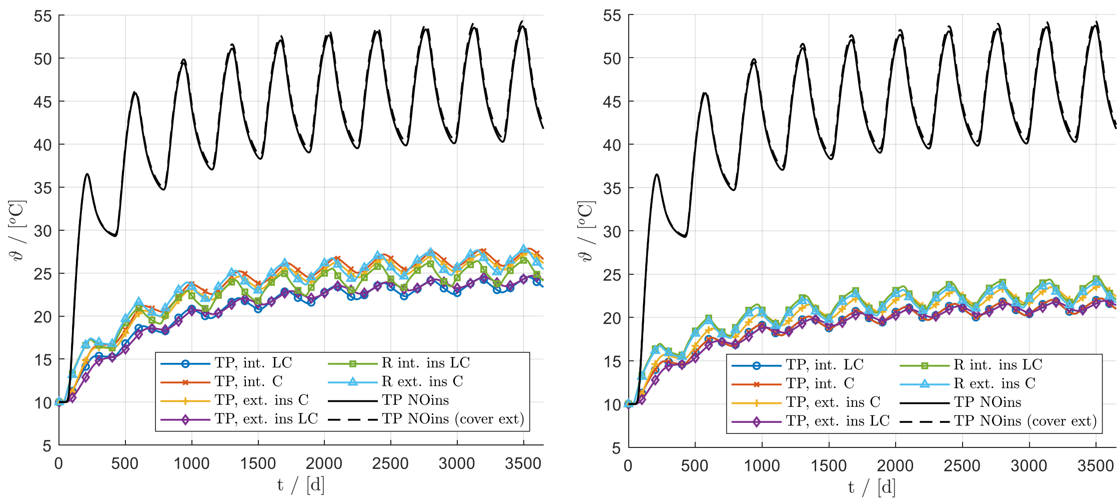

Figure 7: Temperature profile of the ground probe (upper probe) during the investigated time for the 40 500 m³ LTES (seasonal operation) with insulation quality k_{ins}= W/(m·K) and s_{ins}= 1 m and depth up to 50 % of the LTES height (left) and 100 % of the LTES height (right).

3.2. LTES operation

A short-term operation, with a higher number of cycles during the year, leads to higher annual average temperatures in the LTES. This makes the influence of the envelope structure (in terms of insulation location) less visible from the point of view of the LTES outlet temperature. However, the effect of envelope quality and insulation position can still be seen in the ground temperature shown in Figure 8, which presents the same cases as Figure 6. The higher yearly average LTES temperature affects the surrounding ground; higher thermal losses result in a ground temperature approximately 5 K higher than in the case of seasonal operation of the insulated LTES.

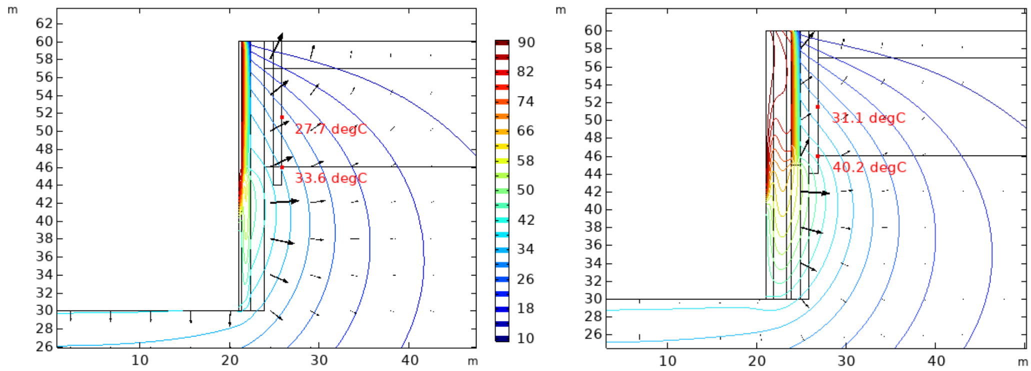

Figure 8: Temperature distribution in the LTES envelope and in the ground in absence of GW for the investigated LTES with insulation quality k_{ins}=0.1 W/(m·K) and s_{ins}=1 m H_{ins}=15 m (50 %), case with internal (left) and external insulation (right).

3.3. LTES size

As reported by several studies (Ochs et al., 2020), increasing the size of the LTES, the reduced area-to-volume ratio ensures more efficient storage and higher efficiencies. The exergy and energy efficiency for the 10th year of operation in seasonal operation mode are presented in Figure 9. The effect on the surrounding ground is however still relevant as visible from the contour plots in Figure 10.

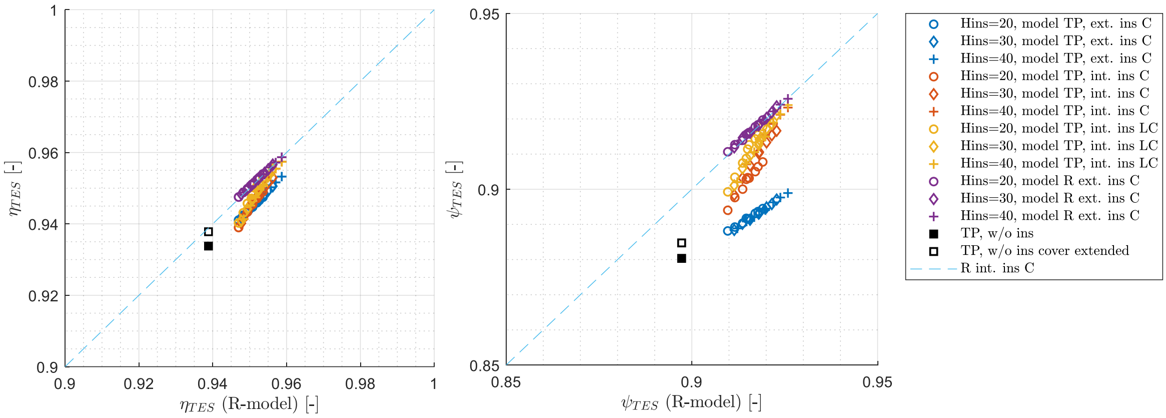

Figure 9: TES energy efficiency (left) and exergy efficiency (right) for the 706 800 m³ LTES. The different colors represent the envelope model approach (TP vs. R), insulation location (int. vs. ext.) and type of concrete filling (C vs. LC), while the symbols distinguish the insulation depth over the LTES height.

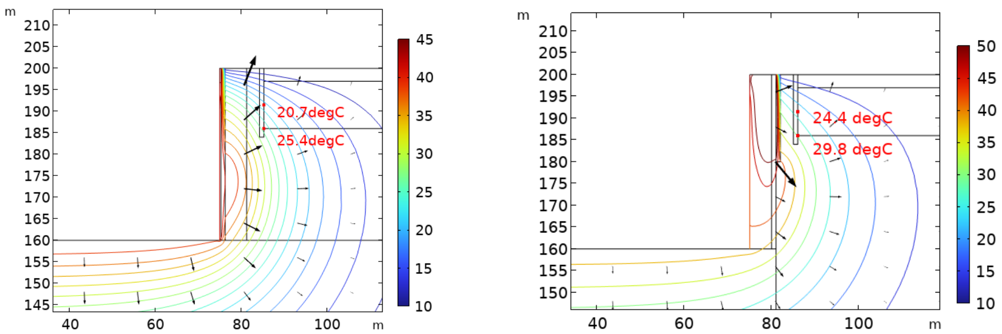

Figure 10: Temperature distribution in the LTES envelope and in the ground in absence of GW for the 706 800 m³ LTES with insulation quality k_{ins}=0.1 W/(m·K) and s_{ins}=1 m, case with internal (left) and external insulation (right).

Conclusions

This works investigates the role of lateral thermal insulation of buries LTES systems. Different variants concerning the insulation location, quality and vertical extension are investigated to analyse the impact on the LTES performance and surrounding ground. In terms of modelling approach, models with resistive (R) envelope and models with detailed geometric/thermophysical (TP) envelope are implemented.

The detailed representation of heat transfer across the different layers of the LTES envelope requires a tool able to discretize the single layers, in order to be sensitive to specific geometry and material variations. FE-based tools allow this discretization, thus being able to couple the numerical model of the LTES water domain and the detailed representation of its envelope and the surrounding soil. Insulation location, vertical extension and quality are investigated. Different KPIs (energy and exergy efficiency, outlet temperatures, ground temperatures) are defined to assess the sensitivity of the model approach.

Purely resistive models are sensitive to insulation quality, but are not able to model the effects of insulation location or 2D heat transfer related to materials (e.g., concrete vs. insulation) or geometrical irregularities (e.g., vertical extension of the insulation). For the same insulation quality, cases with external insulation show lower performance than cases with internal insulation and the corresponding R-models. In particular, the energy efficiency is about 2% lower and the exergy efficiency is 5% lower with external insulation than with internal insulation. Detailed TP models can capture the influence of envelope design on the LTES thermal stratification. For example, the LTES output temperature is lower by about 5 K at the end of the discharge phase in the case of external insulation, for an insulation quality of 0.1 W/(m^2·K).

With these considerations, detailed models of the envelope are a powerful tool to bridge the gap between system-level performance assessment and component-level design optimization. The flexibility of numerical models allows the further integration of GW flow and the modelling of protection measures such as cut-off walls to quantify the effects of GW penetration and the protective effect of cut-off walls.

Acknowledgments

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