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Geotechnical challenges of large-scale PTES in abandoned open-pit mines

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ABSTRACT: Large-scale pit thermal energy storage (PTES) is increasingly recognized as a viable option for seasonal heat storage that can support the transition to low-carbon district-heating systems across Europe. Re-purposing abandoned open-pit mines offers distinct advantages, notably the use of existing excavations that reduce earthworks and surface disturbance, and the possibility of integrating PTES with other renewable energy solutions. Nevertheless, implementation experience is limited so far, and a range of technical, economic, legal, and social barriers must be addressed. Key geotechnical concerns include settlements, slope stability, and buoyancy effects caused by rising post-closure groundwater levels, which can jeopardize structural integrity of the pit and increase heat losses. Moreover, economic viability is challenged by high upfront capital costs and limited long-term performance data. While current research initiatives aim to close these knowledge gaps, recent Ramboll feasibility studies show that early cooperation with mine operators and regulators is crucial to align design with ongoing backfilling and speed up permitting. In combination with new approaches such as low-temperature storage, non-corrosive polymer piping or ash-based embankments, it seems feasible to cut costs, limit re-work, and make PTES in open-pit mines commercially viable.

KEYWORDS: heat storage, lignite mines, post-utilization, slope stability, groundwater.

1 INTRODUCTION

The integration of renewable energy sources into district heating systems is crucial to achieve climate neutrality, but it also requires sufficient capacities of thermal energy storage to overcome daily as well as seasonal gaps between energy supply and demand. Pit Thermal Energy Storage (PTES) presents a promising and affordable solution for storing large amounts of heat from e.g. solar thermal plants, biogas plants, heat pumps or industrial processes to ensure a consistent energy supply throughout all seasons (Xiang et al., 2022). Figure 1 shows a typical example of PTES integration into a district heating system.

Established successfully in Denmark, PTES technology is gaining traction in other European countries such as Germany, Austria or Finland (see Figure 2). To meet regional storage targets, however, PTES must be scaled up significantly, which brings inherent challenges including high area demand and intensive excavation works.

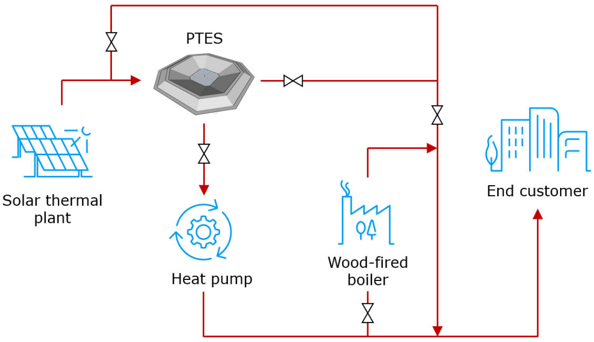

Figure 1. Typical example of PTES integration in a district heating system. A solar thermal plant delivers a major fraction of energy, which is either fed into the grid directly, or stored in a PTES plant in times of surplus energy generation. A heat pump can be used to top up temperature levels to meet grid requirements. Boilers serve as means to smoothen peak demands and therefore support an economic overall system design. Source: Ramboll.

Abandoned open-pit mines, particularly lignite mines being gradually decommissioned in Europe, offer a unique opportunity for large-scale PTES deployment. Utilizing these existing structures can reduce excavation requirements and minimize landscape disruption. Other use cases such as pumped hydropower storage are already investigated for open-pit mines (Kempka et al., 2024) but they require a minimum elevation difference between the two reservoirs. Thermal energy storage in abandoned mines is examined in different pilot studies (Oppelt et al., 2025; Hahn et al., 2023) but is mainly focused on underground mines (MTES). In contrast, little research has been done on PTES in open-pit mines despite the positive effects that large-scale PTES can have on heating systems (Sifnaios et al., 2023a) and its relatively low investment costs compared to other technologies for large-scale thermal energy storage (Schmidt et al., 2018).

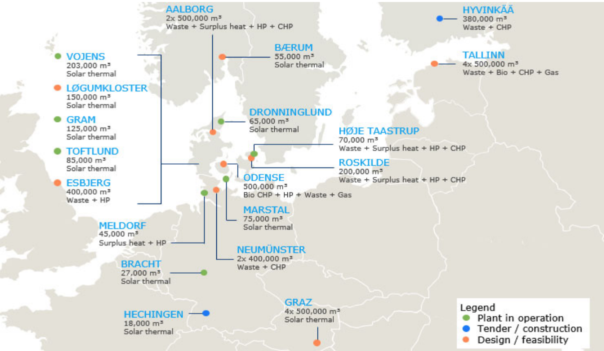

Figure 2. Current PTES systems in Europe that are either in operation, under construction or under feasibility assessment. Source: Ramboll.

This paper provides an overview of the geotechnical challenges associated with PTES in open-pit mines and discusses possible solutions based on practical experiences from industry projects. The aim is to provide basic guidelines for the development of large-scale PTES and to evaluate the need for future research.

2 DESCRIPTION OF PTES TECHNOLOGY

Heat storage has been conducted for many decades, as storing thermal energy represents a suitable means of optimization wherever heat demand and supply are asynchronous. Depending on quantities, storage was typically realized through tanks or containers manufactured as steel or reinforced concrete structures, using potable water as a medium to store heat. However, there are limitations stemming from both technical and economic reasons when scaling up these solutions to meet the growing storage capacity demand.

In the early 2000s, increasing effort was spent to find alternative ways of storing heat, without the use of carbon-intense materials such as reinforced concrete or carbon steel, and with the potential of significant upscaling. These efforts were first conducted in the academic realm, but quickly evolved to first pilot plants in Sweden, Germany and Denmark. The first larger-scale pilot plant of this kind which paved the way to modern PTES technology was established in Marstal (DK) with a water volume of 10,000 m³. Ever since, PTES plants are designed in a similar fashion, and development activities have moved on to focus on specific elements of PTES structures to improve the efficiency and longevity of such plants and thereby increasing competitiveness towards fossil energy sources.

Generally, pit storages are designed as an open pit with sloped sides. Depending on the encountered soil conditions, the slopes are inclined at an angle of approx. 1:2. The ideal base shape is quadratic because it reduces the surface-to-volume ratio while still being technically feasible (in contrast to polygonal or even spherical shapes). However, other shapes have been realized as well to optimize land use within the project boundaries. Preferably, the pit is situated above the groundwater table to simplify the earthworks during the construction phase, but also to reduce potential heat losses during operation.

Once the earthworks are complete and the geometry of the pit is established, the base and the slopes are covered with a plastic liner, usually made of HDPE (high-density polyethylene) with some additives to increase heat resistance. The thickness of these liners is usually taken as 2-2.5 mm, but recent developments even allow up to 3 mm thick membranes. Other materials such as PP (polypropylene) have been successfully implemented as well in established PTES plants. Lining works require suitable environmental conditions to ensure a proper quality of the welds.

The storage pit is then equipped with two or more inlet / outlet structures made of steel (so-called diffusors), distributed across the height of the water body (see Figure 3), typically ranging from 12 m to 15 m depending on the total PTES volume, and other project-specific conditions such as soil strength and groundwater levels. These structures are connected to a heat exchanger which is used for charging and discharging of the PTES plant.

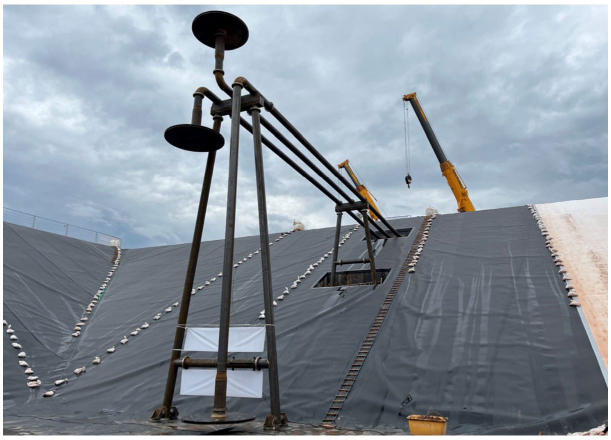

Figure 3. PTES during construction of the inlet / outlet structure, with partially lined slopes. Source: Ramboll.

After completion of the construction work for the basin, it is filled with treated water, i.e. softened, desalinated and alkalinized to a pH value of approx. 10. Water treatment is necessary to reduce or even eliminate any corrosion processes that may harm the inlet and outlet structures as well as the pipes. After flooding the reservoir, a flexible lid consisting of further plastic membranes and insulation (bulk material such as expanded clay can be used as well as heat-resistant insulation panels of various materials) is constructed to avoid exposure of the pit to environmental impacts while reducing heat losses via the water surface.

During operation, the water temperature may reach a maximum of approx. 90°C. Beyond this threshold, operation becomes harmful to the membranes, significantly reducing the PTES lifetime. Also, as the storage is operated under atmospheric conditions, any temperatures close to or even above the boiling point are practically impossible.

The PTES is then charged with heated water during times of surplus energy and discharged when the heat demand exceeds production of the primary heat source in the system. In case of charging, cold water is pumped out through the lower diffusor, warmed up in the heat exchanger and fed back into the storage pit via the upper diffusor. For discharging, the process is reversed. To achieve optimal storage conditions, a distinct thermal stratification within the storage is required. Diffusors are therefore designed such that no turbulence is introduced in the water body during charging and discharging to prevent mixing of hot and cold strata. Otherwise, the thermal gradient between inlet and outlet could be reduced and efficiency of the heat exchanger would decrease. In a worst-case scenario, the temperature of the hot zone in the storage may even be reduced unintentionally to a level below the grid's supply temperature, and the water would need to be re-heated using an additional heat source before it is fed into the grid system.

During periods of charging, the thickness of the hot zone in the upper part increases and the transition zone towards the colder stratum moves downwards. When the storage pit is fully charged, only the lowermost part consists of cold water (see Figure 4). During discharging, the transition zone moves upwards again, and the thickness of cold strata increases. Experience shows that even in large-scale pits, consistent and stable stratification in the water body can be generated and maintained over periods of several months unless the stratification is disturbed by external factors.

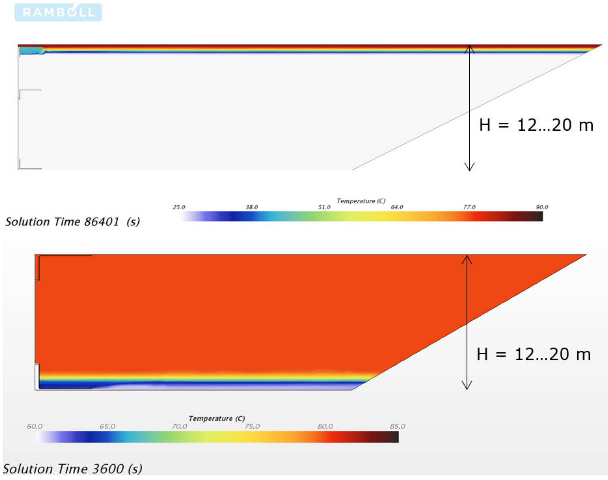

Figure 4. Stratification in a PTES basin at the beginning of charging (top) and discharging process (bottom). White areas indicate water temperatures below 25°C. Laminar flow is ensured through feasible design of the diffusors, depending on charging / discharging rates. Source: Ramboll.

For the operation of PTES, different strategies have been developed and executed in the past. While the standard case is a seasonal operation with one charging and discharging cycle per year, PTES can also be used as a buffer storage with multiple cycles. The latter allows for an increased operational efficiency as heat is stored for shorter periods. However, also one-year cycles result in 80-90% heat recovery with the exact value depending on local boundary conditions, surface-to-volume ratio and technical execution. The optimal operation strategy is identified through detailed analysis of the complete heat supply system.

3 GEOTECHNICAL CHALLENGES

The characteristics of PTES structures generally allow for upscaling to dimensions of up to ~500.000 m³ of water volume. Of course, basins of that size (several hundreds of meters in length and width, depths >20 m) require the availability of vast and flat areas. Combined with the aim of realizing such projects in the vicinity of large heat demand (e.g., municipalities), it is often a challenge to find suitable areas for large-scale PTES. Recently, this challenge has led to an increased interest in abandoned open-pit mines, and first feasibility studies are currently conducted in this context.

However, the integration of PTES systems in abandoned open-pit mines poses numerous geotechnical challenges. Some of these challenges result from general requirements regarding cost optimization and operational feasibility, while others are specifically related to the post-usage of mines or the large scale of PTES implementation.

3.1 *General requirements*

Optimizing geotechnical aspects is essential to reduce costs and enhance operation efficiency of PTES projects. One key strategy is to minimize material and earthwork expenses by ensuring the storage base shape is not strongly oblong. Also, a balanced soil budget of excavation and dam volumes is aimed for to avoid the necessity of purchasing missing soil volumes or removing soil from the site. Keeping the surface area of PTES basins reasonably small is crucial to reduce energy losses during operation. Consequently, dams are usually designed as steep as possible, whilst ensuring sufficient stability of the pit. Construction and maintenance feasibility also dictate design parameters, such as limiting slope angles and incorporating berms for larger basin depths.

Moreover, settlements around foundational areas for the structural parts need to be minimized to an acceptable range, whereas minor deformations on slopes are less critical, as long as these are evenly distributed along the side dams. During construction, timing is an important factor, with lining material typically needing to be installed within a single season to avoid degradation from environmental impacts. Finally, constructing PTES systems within the groundwater should be avoided due to increased costs during construction as well as heat losses, buoyancy forces, and potential environmental impacts on aquifers during operation. All these requirements must be respected and balanced when planning PTES projects.

3.2 *Challenges from post-mining usage*

Soil conditions and groundwater situation differ significantly between greenfield sites and abandoned open-pit mines. In the latter case, soil is represented by backfill material, which is often not compacted and highly heterogeneous. As a result, it often exhibits poor geotechnical properties, leading to issues such as excessive settlements and slope instability. Addressing these issues requires extensive soil improvement measures like compaction, grouting, or stabilization techniques. The specific conditions can vary widely depending on the type and history of the backfill material, necessitating thorough ground investigations and site-specific solutions.

Furthermore, regions of abandoned open-pit mines often exhibit rising groundwater levels which may continue over several decades before a final state is reached, usually in equilibrium with the natural state of surrounding aquifers. This groundwater rise affects the stress state of the soil below and around PTES systems, necessitating a careful risk assessment for large-scale landslides and soil liquefaction (Steiakakis et al., 2024; de Bruyn, 2019). Also, increased heat losses during long-term operation must be considered. The same applies for environmental constraints related to groundwater interactions and contamination, particularly if no separation of the storage reservoir from the groundwater is considered. For a planned PTES project in a former basalt pit in Graz (Austria), large-scale storage without lining is considered already, and the implications of expected chemical interactions between storage water and rock material are currently investigated by the Technical University Graz (https://www.sonnen-speicher.at/). However, feasibility of unsealed storage pits in granular soils with higher hydraulic conductivity has not been assessed yet, and further research is necessary.

3.3 *Logistical challenges*

Additional challenges may result from the fact that PTES construction is done in parallel with ongoing backfill processes of open-pit mines. Besides coordination tasks, there are often uncertainties regarding the availability and suitability of materials for dam construction, requiring flexible planning approaches. The potentially large pit size leads to logistical challenges as well: storage volumes of several million cubic meters impose prolonged construction times which is particularly critical for the installation of the lining. Pits sealed with liners should therefore be split up into units of max. 500,000 m^3 in practice. The increased depth of pits may also necessitate additional berms for stability and maintenance purposes, resulting in additional need for space and material as well as larger lid areas.

Finally, large-scale PTES systems require significant quantities of water for initial filling, adding complexity in terms of time, cost, and availability. This is particularly challenging in regions experiencing low rainfall, where excessive water extraction may lead to conflicting interests.

4 PRACTICAL EXPERIENCE AND CASE STUDIES

4.1 *Ramboll's role in PTES projects*

During the last couple of years, Ramboll has been involved in the planning and construction of several standard-scale PTES projects in Germany (Meldorf, Bracht), Denmark (e.g., Vojens, Gram, Toftlund) and Finland (Hyvinkää). Additionally, some preliminary feasibility studies have been conducted recently for various large-scale PTES projects, including potential projects located in areas of abandoned lignite mines. These feasibility studies included, among others:

- Analysis of geological and hydrogeological conditions at potential storage sites.
- 3D modelling of storage geometry and settlements.
- Cost estimation for construction and selection of a preferred site.
- Assessment of potential ground improvement methods.
- Derivation of optimal storage temperature and volume.

To tackle the geotechnical challenges mentioned above, Ramboll collaborates with industry and research partners. The following paragraphs provide a brief overview of solution strategies, with increased focus on former lignite mines.

4.2 *Practical experiences*

In most cases, mining and backfilling are still ongoing when a potential post-usage for PTES is evaluated. This offers the unique chance to pre-shape storage reservoirs already during backfilling and to reduce time and cost for later earthworks. However, the focus of backfilling is normally on efficient time and space utilization. Typically, material is simply dumped from a certain height, but without any further compaction process involved. Determination of geotechnical parameters during or after backfilling is done only to a minimal degree.

To create the necessary conditions for the construction of PTES plants after backfilling, the infill material must be compacted across a wide area to ensure stability and reduce settlements. A feasibility study conducted for an open-pit lignite mine indicated that vibratory compaction measures would be required within a radius of 30-40 m around the pit. Figure 5 shows the results of a settlement analysis conducted in Plaxis 2D comparing the initial state (before excavation and soil improvement) with the situation immediately after construction as well as long-term changes due to rising groundwater levels. Thereby, installation of a geogrid was assumed between soil and lining material, and improved soil parameters ($\varphi = 35°$, $E_s = 85\ \mathrm{MN/m^2}$) were considered within a radius of 35 m around the pit. However, it must be acknowledged that detailed site-specific soil data was not available, and soil parameters had to be estimated based on literature values, resulting in a wide range of results for best- and worst-case scenarios. For that reason, it was decided to apply the Mohr-Coulomb instead of a more advanced soil model, assuming homogeneous soil conditions with a linear increase of the stiffness module E_s from the surface till the bottom of the pit. The model was also used to investigate slope stability before and after groundwater rise.

In the respective feasibility study, measures for soil improvement resulted in significant costs, making up about 20 – 25% of the total construction costs. However, if the post-usage of standard lignite mines for PTES projects is planned at an early stage, backfilling procedures can be adapted to support construction measures. This is expected to be much more cost-efficient because the amount of earthworks is significantly reduced, and subsequent soil improvement can be minimized or avoided completely.

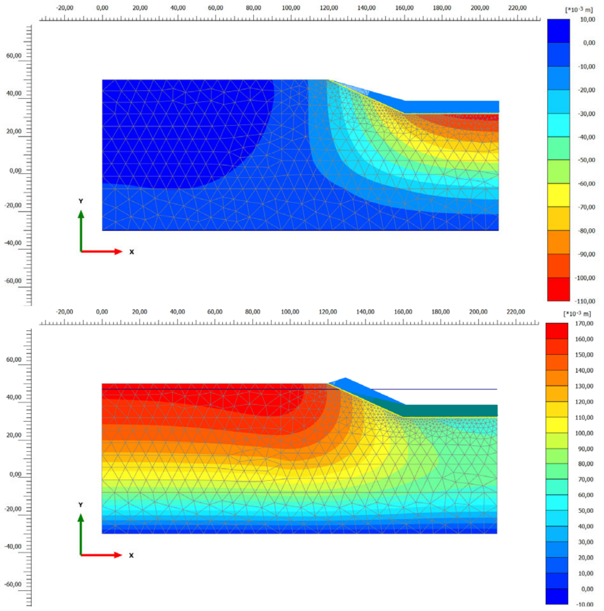

Figure 5. Settlement results for a PTES system in an open-pit lignite mine, assuming soil improvement within a radius of 35 m around the pit. Top picture: Settlements after construction is completed and pit is filled with water. Bottom picture: Heave due to groundwater level increasing to 3 m below surface. Depth of the assessed pit is 18 m. Source: Ramboll.

Early to consider although more relevant for long-term stability and operation of pits in lignite mine areas is the groundwater rise after decommissioning of the abandoned mines. Since this happens over larger time scales of several decades, it is usually not relevant for construction. However, it can lead to significant increase of heat losses once it approaches the pit's elevation (Sifnaios et al., 2023b).

By using numerical models, it can be determined to which degree thermal insulation measures are appropriate to increase efficiency and limit the environmental impact on groundwater (Dahash et al., 2021, 2026). 3D simulations for a standard-scale PTES project in Germany carried out using an in-house tool based on OpenFOAM showed that in the upper part of the storage pit, an additional insulation trench embedded in the dam may be useful to reduce heat losses at the edges, while in the lower part, decreasing storage temperatures lead to reduced heat flow so that from an economic perspective, additional insulation measures would not make sense (see Figure 6).

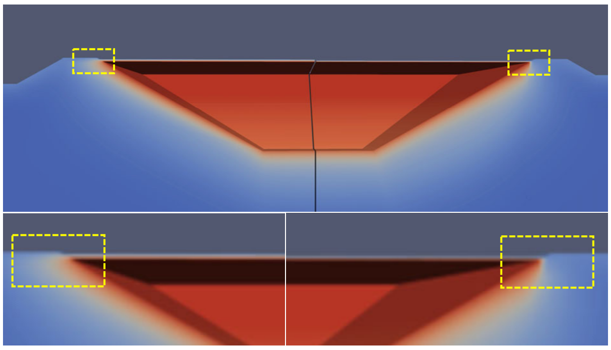

Figure 6. 3D numerical model of a heat storage pit implemented in OpenFOAM (*www.openfoam.org*) simulating heat exchange between a standard-scale PTES plant and the surrounding soil (dam to the left: no additional insulation / dam to the right: insulated trench). The additional effort of building an insulation trench could be proven to reduce heat losses to an extent justifying the initial costs. Source: Ramboll

Figure 7. Execution of the edge insulation proposed based on modelling results. Source: Ramboll.

However, these results cannot necessarily be transferred to large-scale PTES projects and the lack of information on parameters like heat conductivity and heat capacity for abandoned open-pit mines is often even more pronounced than on geotechnical parameters. Also, groundwater flow should be considered because it leads to additional convective heat transport, but this requires information about flow velocities and permeability. If input data is available in reasonable quality and amount, it is planned to investigate the influence of groundwater in future studies in more detail.

In abandoned open-pit mines, buoyancy forces resulting from rising groundwater levels may result in a pit that cannot be pumped out for maintenance (e.g., for replacing liners or steel structures). Different concepts may be considered to deal with the problem, e.g. longer assessment periods or lower storage temperatures that will either lead to increased lifetime of the lining material or even make lining expendable under certain conditions. However, it can also mean that locations are not suitable for PTES or that the bottom of the pit must be moved to a higher level although this is associated with a larger area demand and additional earthwork.

Alternatively, ashes resulting from coal combustion can represent a promising storage environment. The inevitable by-product is usually mixed with carbonate before being stored in separate deposits where it transforms to a nearly impermeable rock with similar material properties as lean concrete. This enables high slope angles and avoids settlement problems. Also, as hydration processes are exothermic, the increased temperature of the ash monolith could result in reduced heat losses or even an additional gain of heat energy over several years, especially during the initial operational period before a long-term heat equilibrium with the ambient solid ground is achieved.

Finally, impermeability of the embankment material could lead to a significant reduction of installation costs as lining may be expendable for the slopes and the bottom of the pit, leaving only the floating insulation cover requiring lining material. However, it is essential to consider a potential post-usage for PTES already during the backfilling phase as the hardened ash is difficult to shape. This requires early involvement of different stakeholders, such as mine operators, mining authorities and local communities, to modify the existing reuse scheme. Figure 8 shows an example of a 3D pit model developed as part of a feasibility study. The aim of the study was to optimize the current backfilling scheme proposed by the mining operators such that excess material could be used to create several PTES basins. While the grey areas show the optimized backfill monolith that is required to support an unstable slope of the abandoned mine, the dams marked in yellow could be constructed using the “saved” ashes. The size of the individual PTES modules can be adapted to the requirements of a targeted operational strategy that involves actual heat supply and demand scenarios defined by the client.

Figure 8. Top: Backfilling of an abandoned lignite mine. Bottom: Example of a 3D model showing the storage geometry of a modular PTES setup in an abandoned pit mine with (source: Ramboll).

Generally, changing existing plans for (post-) mining operations and usage is a time-consuming task and associated with similar challenges as the geotechnical planning. Nevertheless, it must be handled with great care because local acceptance and the knowledge of mining operators about local ground conditions are of great value. Their data and experience are often the only source of information to derive soil parameters and make reasonable assumptions for feasibility studies. Thus, early exchange and good collaboration with local stakeholders significantly increases the chances for a successful implementation of PTES projects.

5 DISCUSSION

The growing interest in large-scale PTES, particularly in decommissioned or expiring lignite mines, underlines the importance of addressing geotechnical factors essential for cost efficiency and site selection. The most relevant challenges include settlements, slope stability, and rising groundwater.

These challenges are associated with significant costs, project execution durations, and other limitations such as extensive soil improvement, reduced slope angles, large buoyancy forces, and increased heat losses.

Effectively managing these aspects requires early planning and good communication between stakeholders. In the initial planning phases, the lack of information about geotechnical and hydrogeological parameters makes reliable statements and site selection difficult. Hence, early involvement of mining operators is crucial. Their knowledge of mining and restoration processes, soil, and groundwater conditions is instrumental to assess potential storage geometries and cost projections for soil improvement, earthworks, and insulation.

Mining operators also play a critical role in aligning PTES design with ongoing backfilling processes and identifying areas of concern regarding slope stability. Another essential stakeholder are mining authorities, as adapting backfilling strategies and reuse schemes requires their permission. Early involvement of mining authorities allows addressing potential concerns about geotechnical safety and environmental protection. Pre-shaping storage geometries during backfilling is vital to save costs and time for construction measures and soil improvement. However, adjusting existing plans for (post-) mining operations and usage requires flexibility and openness from involved parties and stakeholders.

Planners of PTES plants must therefore also be capable and willing to follow new ideas and create innovative technical solutions to address the specific challenges, such as:

- Considering alternative lining materials or even strategies without lining to reduce costs as well as installation and maintenance risks.
- Combining reduced storage temperatures with larger pit sizes to decrease heat losses and increase lifetime.
- Expanding the choice of inlet / outlet structures to non-corrosive materials like plastics (HDPE, LLDPE, PP) to extend maintenance intervals.
- Utilizing combustion ashes for storage embankments and bases if available in large quantities.
- Developing new technical solutions for lid construction to accommodate large dimensions and reduce effort during potential overhaul phases.

Of course, these new approaches need to be backed with reliable datasets as well as research on modelling and field scale. Thus, the design phase of any large-scale PTES project should include detailed investigations and careful design as well as field tests and accompanying monitoring measures. This ensures structural integrity and operational efficiency of PTES systems and optimized PTES design for future projects.

6 CONCLUSIONS AND OUTLOOK

Research indicates that large-scale PTES can effectively address the high demand for seasonal heat storage associated with the transition to green energy in many regions in Europe, but also worldwide. Despite the promising aspects, practical implementation experience remains limited, posing technical, economic, legal, and social challenges. Ongoing research, such as the TREASURE project (https://www.treasure-project.eu), seeks to address these issues, though specific challenges related to PTES in abandoned open-pit mines are not thoroughly studied yet.

PTES projects in former lignite mines face geotechnical and hydrogeological challenges, including settlements and slope stability due to poor backfill material properties. Rising groundwater levels after mine closure contribute to buoyancy forces, altered stress states, and increased heat losses. Addressing these issues is essential for advancing PTES technology in mining areas, requiring comprehensive approaches integrating practical experiences, advanced design solutions, and ongoing research.

Ramboll's experience highlights the importance of early planning and communication between stakeholders for successful project implementation. Collaboration with mining operators is vital for feasibility evaluation and optimizing site selection, demanding permits to adjust reuse schemes. Aligning PTES design with ongoing backfilling ensures cost efficiency. Utilizing pre-shaped pits and alternative backfill materials like combustion ashes can significantly reduce construction time and costs. Flexibility and openness to new design solutions are crucial for expanding PTES applications to abandoned open-pit mines, as approaches derived based on greenfield scenarios may not always suffice.

Further research is necessary to assess slope stability and heat exchange between pits and the surrounding soil, as well as the impact of high groundwater tables, including consideration of environmental impacts. New and improved heat-resistant lining designs are required to reduce life-cycle costs by extending operational periods, potentially even eliminating the need for pit drainage for refurbishment activities. Lastly, addressing social constraints is crucial for securing broader acceptance and enabling PTES technology to become a pivotal element in the renewable energy transition.

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