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(ES TCP)

Task 45 - Accelerating the uptake of Large Thermal Energy Storages

Subtask 4: Dissemination

**Deliverable 4.1.1: Inventory of novel large thermal energy
storage concepts - Overview**

AUTHORS

Romain Sucche, PlanEnergi

Geoffroy Gauthier, PlanEnergi

Morten Vang Bobach, Bobach Solutions

Jan Bergland, Hydroc

Timm Sievers, Solmax Geosynthetics GmbH

Thomas Labda, Solmax Geosynthetics GmbH

Catrin Tarnowski, Solmax Geosynthetics GmbH

Lukas Seib, Technical University of Darmstadt

Bas Godschalk, DTESS

Jan Bergland, HYDROC

CONTRIBUTORS

Maria Moser, Solid

Christian Hofer, Bilfinger

Nikolas Salomaa, NollaE

Toivo Koskinen, Business Turku

Thorsten Urbaneck, Technische Universität Chemnitz

Abdulrahman Dahash, AIT Austrian Institute of Technology

Sverre Tragethon, Hallingplast

Davide Righini, HYDRA

Thomas Schmidt, Solites

Jörn Falbe, Unitank

Jan Jette Blangé, Canopus Drilling Solutions

Raimo Vuopionperä, (EUI03-111) Nordic Energy Capital (project), City of Vaasa, Finland

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LIST OF ABBREVIATIONS

Countries

| | | | |
|----|-------------|-----|-------------|
| AT | Austria | FIN | Finland |
| BE | Belgium | IT | Italy |
| CH | Switzerland | NL | Netherlands |
| DE | Germany | NO | Norway |
| DK | Denmark | SE | Sweden |

| | |
|---------|--|
| ATES | Aquifer thermal energy storage |
| BHE | Borehole heat exchanger |
| BTES | Borehole thermal energy storage |
| CFB | Concrete Floating Bodies |
| CTES | Cavern thermal energy storage |
| DH | District heating |
| DHN | District heating network |
| DSSD | Directional Steel Shot Drilling |
| HT-ATES | High temperature aquifer thermal energy storage |
| KPIs | Key performance indicators |
| LTES | Large thermal energy storage |
| MD-BTES | Medium-deep borehole thermal energy storage |
| MT-ATES | Medium temperature aquifer thermal energy storage |
| MTES | Mine thermal energy storage |
| PDC | Polycrystalline diamond cutter |
| PP | Polypropylene |
| PTES | Pit thermal energy storage |
| R&D | Research and development |
| SKEWS | Saisonal Kristalliner ErdWärmeSondenspeicher (seasonal crystal BTES) |
| TES | Thermal energy storage |
| TRL | Technology readiness level |
| TTES | Tank thermal energy storage |
| WGTES | Water gravel thermal energy storage |

INTRODUCTION

1 Background

Large thermal energy storage (LTES) systems are key components to provide flexibility to district heating and cooling systems and to enable a renewable-based thermal energy provision. The International Energy Agency Technology Collaboration Programme on Energy Storage (IEA TCP ES) identified this key position of LTES and decided to start Task 39 on Large thermal Energy Storage Technologies for District Heating¹. It gathered LTES experts from several countries that worked on numerical simulation, materials for LTES, on Key Performance Indicators (KPIs) and on generating and disseminating knowledge on LTES.

As part of IEA-ES Task 39, [a comprehensive list of more than 100 LTES projects was created](#), including the 4 most common and mature technologies: Tank TES (TTES), Pit TES (PTES), Aquifer TES (ATES) and Borehole TES (BTES).

Also in Task 39, LTES systems were defined as sensible Thermal Energy Storages (TES) that:

- Are designed to store at least 1 GWh of heat per year²,
- Operate at atmospheric pressure, meaning they are non-pressurized systems,
- Provide stored heat suitable for discharge into District Heating Networks (DHN) at temperatures above 50°C.

In 2024, Task 45 continued the works started in Task 39, now aimed at preparing grounds for an acceleration of LTES technologies.

2 Purpose of the inventory

IEA-ES Task 45 also extends the scope beyond the initial definition of LTES technologies. The objective is to explore ongoing developments in novel LTES concepts across different levels of technological maturity. These novel concepts include (but are not limited to):

- LTES with elevated storage temperatures (e.g. pressurized systems, cavern thermal energy storage, high-temperature ATES, rock or sand storage),
- LTES using existing infrastructures (e.g. gas/oil reservoirs, mines, quarries, gravel pits),
- Use of different/new materials (e.g. high-temperature resistant geomembranes),
- New design of existing technology (e.g. PTES with multi-purpose lid),
- New R&D projects or concepts, etc.

The technical and industrial development status of these novel or novel LTES technologies have been gathered and structured within this report.

¹ <https://iea-es.org/task-39/>

² As either a “seasonal storage” with a large capacity (GWh-scale) charged/discharged once or twice a year or a “daily/weekly storage” with multiple charge/discharge cycles per year and a smaller capacity (10 MWh-scale)

3 Method

The inventory of novel LTES concepts was developed using two complementary approaches³: a structured stakeholder questionnaire and direct outreach to selected experts. All collected information was then consolidated into a single inventory, classified by technology category, and enriched with contextual descriptions, examples, Technology Readiness Level⁴ (TRL) assessment, and assignment to one of seven improvement categories⁵.

The assigned TRL refers specifically to the maturity of the underlying technology improvement/innovation, rather than to the overall storage technology. For instance, if the improvement concerns a new drilling technique for a BTES system, the TRL will correspond to the maturity of that drilling technique itself, rather than to the BTES technology as a whole.

INVENTORY OF NOVEL LTES CONCEPTS

This section begins with a general overview of the identified novel LTES concepts. It then presents a consolidated summary of the inventory in a single table, highlighting the key information. Finally, a detailed inventory is provided, describing each novel concept along with the context in which it offers an improvement, the proposed solution, and one or more examples of its implementation.

1 General overview of the novel LTES concepts

Overall, 27 novel concepts have been identified, covering 6 categories of LTES technologies: TTES, PTES, BTES, ATES, Cavern TES (CTES), and Mine TES (MTES).

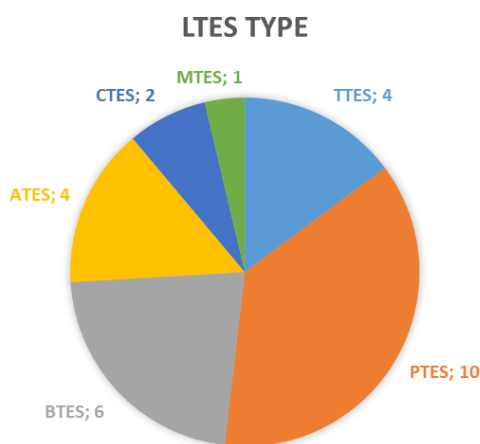


Figure 1: Distribution of the LTES technology categories of the novel concepts

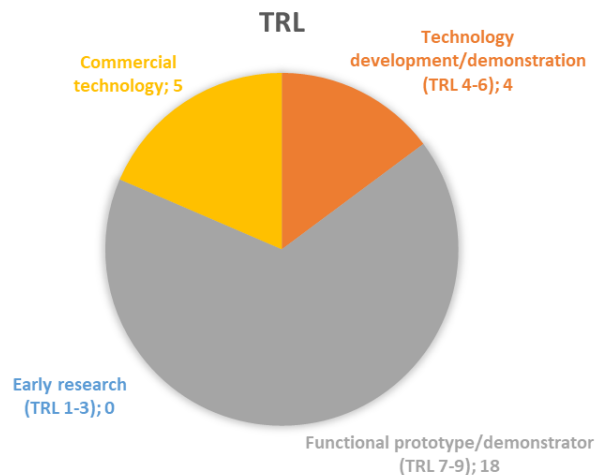


Figure 2: Distribution of the TRLs of the novel concepts

As shown in Figure 1, the technologies PTES, BTES, ATES, and TTES are the most dominant technologies, with 10, 6, 4, and 4 novel concepts identified, respectively. This distribution highlights a strong

³ More information about the Method can be found in Appendix

⁴ More information about the TRL can be found in Appendix

⁵ Defined in the next section

level of innovation activity within these relatively mature technologies. In contrast, CTES and MTES are less mature and emerging technologies, with only one novel concept identified for each.

Figure 2 presents the TRL distribution of the novel concepts. Most of the concepts are characterized by relatively high TRLs, corresponding either to commercial technologies or to functional prototypes and demonstrators with TRLs above 7. This indicates that the majority of the identified improvements are already well advanced and have been tested either in demonstration projects or in full-scale commercial applications. Only 4 concepts fall within the TRL range of 4–6, indicating an ongoing technology development stage. No novel concepts were identified at the early research phase, which is a bit intentional, as the focus of this inventory is on concepts that have already demonstrated a certain level of technical maturity and operational feasibility.

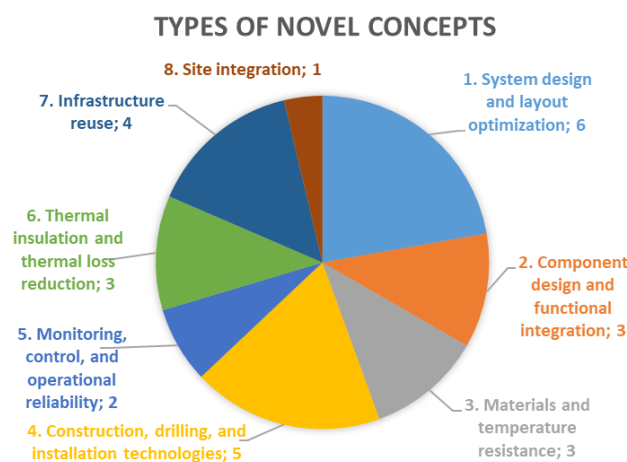


Figure 3: Distribution of the types of novel concepts

Figure 3 illustrates the distribution of the novel concepts across seven categories of improvement, which are listed and described in the following sections.

1. System design and layout optimization

System design and layout optimization focuses on improving the overall configuration and geometry of the TES system to enhance performance and efficiency. It includes the development of concepts such as pressurized or multi-zone storage, optimized surface area-to-volume and aspect ratios, and the functional use of system surfaces. The objective is to increase useful storage capacity, reduce thermal losses at system level, and improve the integration between thermal energy sources, storage, and demand.

2. Component design and functional integration

Component⁶ design and functional integration address the performance and interaction of individual system elements within the storage concept. This type of improvement includes the design of charging and discharging pipes, diffusers, lids, penetrations, drainage layers, and pumping solutions. The aim is

⁶ In this report, “component” refers to different levels of sub-systems of an LTES technology. In IEA ES Task 39, components was limited to the individuals components themselves (such as piping, insulation layer, floating liner, temperature measurement equipment), while “system” referred to the functional element (lid, piping system, boreholes, pit, measurement system). Here, components includes both individual components and functional elements

to ensure reliable operation, improved flow distribution, reduced hydraulic losses, durability and robust functionality under varying operating conditions.

3. Materials and temperature resistance

Materials and temperature resistance improvements focus on developing and applying materials that can withstand higher operating temperatures, thermal cycling, and long-term exposure to aggressive environments. This includes high-temperature-resistant geomembranes, polymers, protection layers, and injection components. The purpose is to enable higher storage temperatures, extend system service lifetime, potentially increase useful energy storage capacity, and maintain safety and performance over time.

4. Construction, drilling, and installation technologies

Construction, drilling, and installation technologies relate to the methods used to build and implement LTES systems. This type of improvement includes advanced drilling techniques, deeper or horizontal boreholes, bedrock fracturing, and innovative installation approaches. These developments aim to reduce construction risks and costs, improve feasibility in challenging geological conditions, and expand the range of suitable sites.

5. Monitoring, control, and operational reliability

Monitoring, control, and operational reliability improvements enhance the ability to observe, manage, and safely operate LTES systems over time. They include advanced temperature measurement systems, leakage detection technologies, and flexible operational strategies such as variable pump operation. The goal is to ensure stable performance, early fault detection, and efficient operation under dynamic load and temperature conditions.

6. Thermal insulation and thermal loss reduction

Thermal insulation and thermal loss reduction focus on minimizing energy losses from storage volumes, wells, boreholes, and associated infrastructure. This includes insulation of sidewalls, bottoms, lids, boreholes, and pipes, as well as optimized design to avoid thermal bridges. These measures directly increase storage efficiency, prolong heat retention, and improve the overall energy balance of the system.

7. Infrastructure reuse

Infrastructure reuse focuses on adapting existing assets for LTES applications. This includes converting old tanks, mines, or caverns and reusing other available structures to reduce the need for new construction. The benefits can be multiple: reduce investment costs, shorten implementation timeline, lower the environmental impact, and increase the acceptance of storage projects.

8. Site integration

Site integration improvements aim to tailor LTES systems to local conditions and environmental constraints. This involves designing systems that account for factors such as rainfall, snow loads, and other climate-related challenges.

2 Inventory summary

Table 1 is a summary of the inventory of all LTES novel concepts identified.

Table 1: Summary of the inventory of novel LTES concepts

| LTES category | Identified novel concepts | Improvement type | TRL | Solution summary | Example |
|---------------|--|---|-----|---|--|
| TTES | Higher temperature, using pressurized TTES | 1. System design and layout | 9 | Pressurized tanks allow water storage above 100°C, increasing energy density and enabling higher storage temperature | Avedøreværket (DK): two 22'000 m ³ pressurized TTES operating up to 115°C for DH |
| | Higher temperature, using 2-zone TTES | 1. System design and layout | 9 | Vertically stacked tanks separate high-temperature pressurized zone and atmospheric buffer zone | Leipzig, Duisburg, Heidelberg, Kiel (DE): multiple 2-zone TTES operating up to 120°C |
| | Conversion of old tanks into TTES | 7. Infrastructure reuse | 9 | Existing oil tanks retrofitted with structural adjustment, insulation, diffusers, and instrumentation for thermal storage | Hanover (DE): former heavy-oil tank converted into ~15'000 m ³ TTES connected to DHN |
| | Co-utilisation of the top or sides of a TTES | 1. System design and layout | 9 | Tank surfaces used for photovoltaics, public access, or architectural functions beyond thermal storage | Dornbirn (AT): TTES with photovoltaic façade; Heidelberg (DE): rooftop restaurant |
| PTES | Improved volume-to-surface area ratio for PTES geometry | 1. System design and layout | 7-9 | Steeper embankments increase storage volume while reducing cover area, space usage and thermal losses | Rechlin (DE): 70° slope PTES achieved 33% higher volume than conventional design |
| | Novel and improved systems for leak detection and temperature measurements | 5. Monitoring, control, and operational reliability | 7-9 | Electrical and fiber-optic systems enable early leakage detection and distributed temperature monitoring | Rechlin (DE): electrical and fibre-optic systems installed in demonstration PTES |
| | Thermal insulation on the bottom and embankments of the PTES | 6. Thermal insulation and heat loss reduction | 7-9 | Advanced insulation materials reduce conductive thermal losses to soil and groundwater | Rechlin (DE): spray-on, bulk, and board insulation tested with extensive monitoring, Steinfurt (DE), Eggenstein-Leopoldshafen (DE) |
| | Polymer penetration structure and polymer charging and discharging pipes, including diffusers | 2. Component design and functional integration | 7-9 | Polymer penetrations and pipes replace concrete and steel, simplifying construction and reducing corrosion risks | Rechlin (DE): polymer diffusers and penetrations installed and monitored during operation |
| | Improved high temperature resistant PE-RT geomembranes for higher operating temperatures in PTES | 3. Materials and temperature resistance | 7-9 | New PE-RT liners designed for reliable operation at up to 95 °C with an expected service life of ~30 years based on laboratory-tested aging performance | Rechlin (DE): PE-RT geomembranes installed in 2'000 and 3'000 m ³ PTES test pits |
| | Newly developed high temperature resistant protection and drainage layers | 3. Materials and temperature resistance | 7-9 | Heat-resistant geotextile and geonet layers protect liners and manage moisture and vapor | Rechlin (DE): protection and drainage layers installed beneath geomembrane and lid |
| | Improved lid design for rainwater and moisture (vapor) management | 2. Component design and functional integration | 7-9 | Revised floating lid integrates drainage, insulation, leak detection, and moisture control | Rechlin (DE): improved lid implemented on one demonstration PTES |
| | Reuse of existing infrastructures & sites | 7. Infrastructure reuse | 7-9 | PTES built in quarries, basins, landfills, or gravel pits to reduce excavation and land use | Ingolstadt (DE); Weitendorf (AT); Deonninglund (DK); Hechingen (DE); Hyvinkää (FIN) |
| | Lid design to comply with local climate (severe cold climate) | 8. Site integration | 7-9 | Structural insulated lids designed for local snow, wind, and cold temperatures | Hyvinkää (FIN): 380'000 m ³ PTES designed for severe climate conditions such as heavy snow load and low ambient temperatures |
| | PTES design enabling multifunctional use of the system's top surface | 1. System design and layout | 7-9 | Multifunctional PTES surfaces require extra structural measures—such as CFB modules, a dedicated load-bearing structure, or a gravel–water medium—to safely support heavy surface uses. | Steinfurt, Chemnitz, Eggenstein (DE): gravel-water storage medium, respectively featuring a private garden, a road, and a schoolyard on the PTES lid |

| LTES category | Identified novel concepts | Improvement type | TRL | Solution summary | Example |
|---------------|---|--|-----|--|--|
| BTES | Innovative layered piping solutions | 2. Component design and functional integration | 4-6 | Multi-layer high-temperature borehole pipes improve durability and oxygen tightness | No example yet, only lab-scale testings so far |
| | Deeper boreholes for BTES with reduced thermal losses and surface occupancy | 4. Construction, drilling, and installation technologies | 7-9 | Fewer, deeper boreholes reduce surface footprint and limit shallow groundwater impact | Darmstadt (DE): three 750 m deep boreholes forming a medium-deep BTES |
| | Thermal insulation of the borehole | 6. Thermal insulation and thermal loss reduction | 7-9 | Low-conductivity grout and liners reduce thermal losses in upper borehole sections | Darmstadt (DE): insulated boreholes using ThermoCem grout and polypropylene liners, Crailsheim (DE) |
| | Use of the top surface of the BTES system as a combined heat source & sink | 1. System design and layout | 7-9 | Surface piping collects solar heat for storage while providing cooling to the surface during operation | Turku (FIN): market square BTES with over 700 energy piles |
| | Fracturing of bedrock | 4. Construction, drilling, and installation technologies | 4-6 | Micro-hydraulic stimulation creates connected fractures for efficient bedrock heat storage | Linköping (SE): pilot fractured-bedrock storage connected to district heating |
| | Directional steel shot drilling for deeper and steerable Borehole Heat Exchangers (BHE) | 4. Construction, drilling, and installation technologies | 7-9 | Steel shot-assisted drilling combined with PDC cutters enables directional control, reduced mechanical stress, and efficient drilling of deeper curved boreholes | Delft (NL): Successful DSSD pilot in 2025. Ten curved BHEs from 20x30m ² area produce 1000 MWh/yr (GHEtool) |
| ATES | Insulated well pipes | 6. Thermal insulation and thermal loss reduction | 4-6 | Insulation reduces thermal losses during hot-water injection and extraction in ATES wells | Delft (NL); Andel (NL): insulation options evaluated for HT- and MT-ATES |
| | Temperature resistant injection components | 3. Materials and temperature resistance | 7-9 | High-temperature and corrosion-resistant well components enable hotter ATES operation | Delft (NL): upgraded injection components for ~90°C operation |
| | Well pump flexibility (on-off cycles) | 5. Monitoring, control, and operational reliability | 7-9 | Pumps designed for frequent cycling and high temperatures improve operational flexibility | Delft (NL): pump selection optimized for flexible ATES operation |
| | Advanced drilling technologies | 4. Construction, drilling, and installation technologies | 7-9 | Casing-based drilling with interchangeable tools and remote control enables faster, safer, and more efficient well construction in challenging ground conditions | Riva del Garda (IT): advanced drilling planned for deep ATES wells |
| CTES | Underground thermal energy storage in artificial caverns | 4. Construction, drilling, and installation technologies | 7-9 | Artificial rock caverns store hot water at elevated temperatures (because of increased pressure) for large-scale seasonal and short-term storage | Vantaa (FIN): VARANTO cavern storage concept integrated with DH |
| | Conversion of old oil caverns into TES | 7. Infrastructure reuse | 9 | Convert former oil caverns into thermal storage through feasibility assessment, cleaning, equipment installation, and water filling. | Vaasa (FIN), Västerås (SE): conversion of old heating oil caverns into CTES |
| MTES | Thermal energy storage using former mine infrastructure | 7. Infrastructure reuse | 4-6 | Flooded mines reused as large-scale thermal storage using mine water circulation | Bochum (DE): abandoned coal mine tested as MTES |

CONCLUSION

A total of 27 cases were identified as novel concepts of LTES technologies. These concepts represent potential deviations from conventional LTES designs and reflect the ways in which existing approaches can be adapted or enhanced.

As the importance of LTES for energy system flexibility and decarbonisation becomes increasingly evident, a growing number of new concepts has emerged. Active participation by companies, universities, and research organisations in this field demonstrates the rising attractiveness of LTES. This includes the clear need to improve their performance, to address the limitations of current designs, to better account for both local and general constraints (such as urban integration, operation under snow or harsh climatic conditions, or deployment within existing infrastructures), and to adapt the technology to specific needs (e.g. reduced land use).

Overall, two main types of improvements can be distinguished. The first type builds upon existing concepts and extends mature technologies such as PTES, BTES, ATES, and TTES. The second type consists of more innovative concepts, that have not yet been implemented in practice, such as TES in newly built caverns, or in abandoned/decommissioned caverns/mines.

The identified novel concepts are generally associated with relatively high TRLs, corresponding either to commercial solutions or to functional prototypes and demonstrators. This indicates that most of the proposed improvements are already well advanced and have been validated through demonstration projects or full-scale commercial applications.

The novel concepts were grouped into eight types that reflect the main areas in which LTES systems can be enhanced. These categories cover improvements at both system and component level, including optimized system design and layout to increase usable storage capacity and reduce thermal losses, as well as better integration and performance of individual components to ensure reliable and efficient operation. Further improvements address the use of advanced materials capable of withstanding higher temperatures and long-term thermal stress, alongside innovations in construction, drilling, and installation techniques that expand feasibility and reduce costs in complex geological conditions. Additional categories focus on enhanced monitoring, control, and operational strategies to ensure safe and stable performance over time, measures to reduce thermal losses through improved thermal insulation, and approaches for better site integration and reuse of existing infrastructure. Together, these categories provide a comprehensive framework for understanding how technical, operational, and site-specific improvements can increase the integration, efficiency, robustness, and applicability of TES systems, and aim to limit the visual, spatial, or environmental impacts of the LTES.

This inventory does not aim to be exhaustive, as many additional novel concepts and examples likely exist beyond those identified. Access to detailed technical information is often limited, mainly due to the confidentiality of ongoing commercial projects and the fact that some innovations are still under development and not yet fully implemented or publicly communicated. Moreover, it is important to note that not all novel concepts identified in this inventory are expected to reach market deployment. Some may prove to be insufficiently cost-effective, while others may face technical or legal limitations when scaled up to large-scale applications. Close collaboration between local authorities and project developers/technical teams can, however, help identify solutions that are better adapted to specific local conditions and constraints.