IEA-ES Task 39: Large Thermal Energy Storages for District Heating

Final report

Aerial view of the 70’000 m^3 Pit Thermal Energy Storage owned by Høje Taastrup District Heating and VEKS
Photo: Ioannis Sifnaios

This report covers the Danish contribution to the project originally called “IEA-ECES Annex 39”, and later renamed to “IEA-ES Task 39” following a reorganization of naming conventions at the International Energy Agency (IEA). It is related to the Energy Storage Technology Collaboration Programme (ES-TCP) of the IEA.

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- EUDP project number: 64020-2036
- Project partners of the Danish consortium: PlanEnergi, DTU Construct, Rambøll & Aalborg CSP

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1. Project details

Project title	IEA-ES Task 39 Large Thermal Energy Storages for District Heating
File no.	64020-2036
Name of the funding scheme	EUDP
Project managing company / institution	PlanEnergi
CVR number (central business register)	7403 8212
Project partners	PlanEnergi, DTU construct, Aalborg CSP, Rambøll
Submission date	24 January 2024

2. Summary

2.1 English summary

IEA-ES Task 39 has been working on 4 major thermal storage technologies (Tanks, TTES, Pits, PTES, Bore-holes, BTES and Aquifers, ATES). A definition for LTES (Large Thermal Energy Storages), which sets a clear framework for what can be called "Large Thermal Energy Storages", has been developed. The definition contains, among other things, criteria for how the heat is stored and minimum annual stored energy.

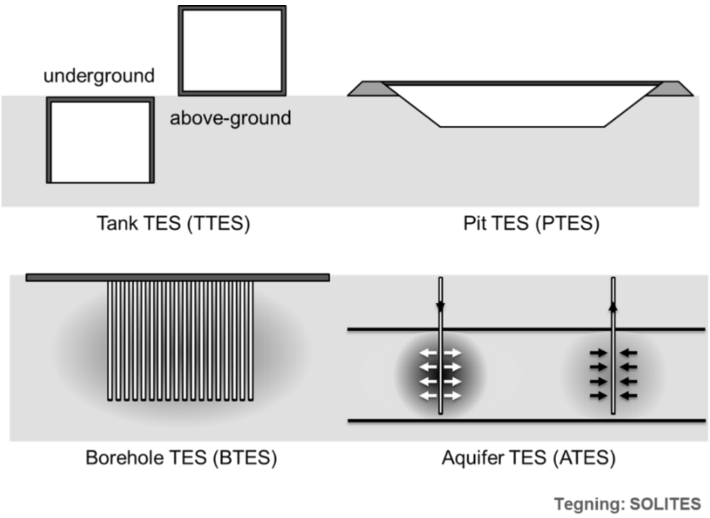

Figure 1. “Sketch_4_LTES_Types.png”

Task 39 has identified the 4 main stages that LTES projects go through, and its objective has been to share tools, references and methods to guide specific actors: policy makers, scientists & engineers, and project developers & project owners.

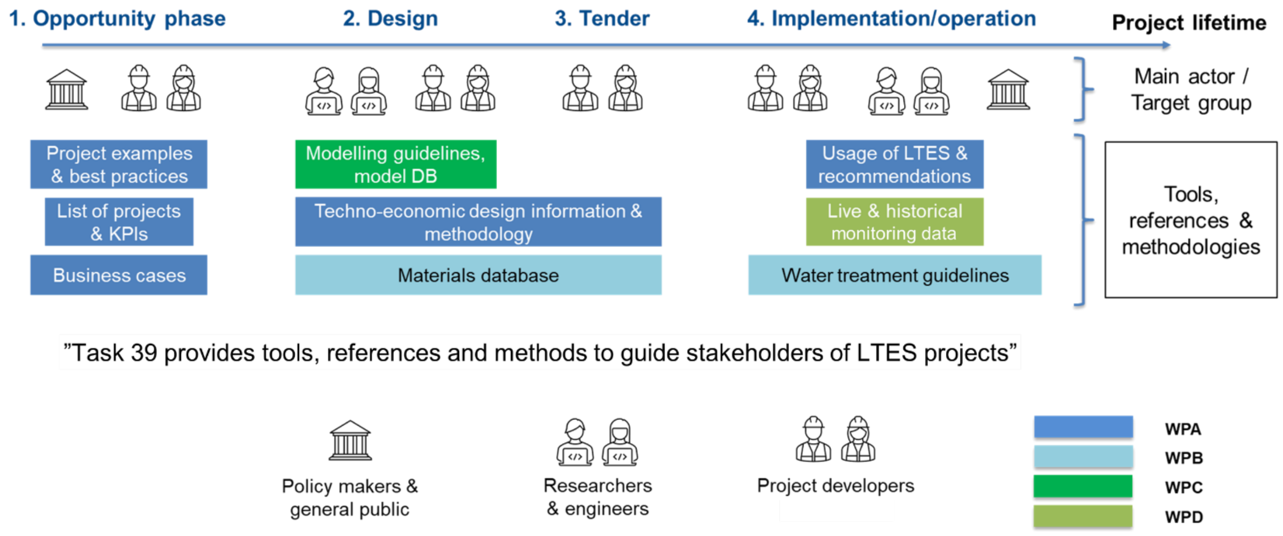

Figure 2. "Diagram_LTES_project_stages.png"

The task's objective has been fulfilled by developing dissemination materials for all 4 stages, using results from 4 work packages (A: application scenarios, B: Components and materials database, C: Round robin simulations, D: Knowledge base for decision makers).

Information material/deliverables will be available on the Task's website: https://iea-es.org/task-39/ showing:

A- what LTES are, what they look like, what they are used for, some references and examples of LTES projects (use cases). A guide to LTES project development has also been created
B- a draft database for materials and components used in LTES, as well as a reference for necessary water quality. The database contains the information that has been studied for different LTES technologies, as well as a guide to further development of the database
C- how to test different modelling tools for all 4 LTES technologies. A precise guide to the test method has been developed, as well as templates for results, a list of available modelling tools and the analysis/comparison of the results from the 1st phase calculations
D- what has been done during the project, through update emails, presentations during international conferences and online webinars, as well as a closing workshop, held in December 2023

2.2 Danish summary

IEA-ES Task 39 har arbejdet på 4 store varmelagreteknologier (akkumuleringstanke, TTES, damvarmelagre, PTES, borhulslagre, BTES og akviferlagre, ATES). En definition for LTES (Large Thermal Energy Storages), som sætter klare rammer for hvad man kan kalde "store varmelagre", er blevet udviklet. Definitionen indeholder bl.a. kriterier for hvordan varmen bliver lageret og minimum årlig opbevaret energi.

Figure 1. "Sketch_4_LTES_Types.png"

Task 39 har identificeret de 4 hovedfaser som LTES-projekter gennemgår, og har haft som formål at dele værktøjer, referencer og metoder til at vejlede specifikke aktører: politiske beslutningstagere, forskere & ingeniører, og projektudvikler & projektejere.

Figure 2. "Diagram_LTES_project_stages.png"

Task'ens formål er blevet opfyldt ved at udvikle formidlingsmaterialer for alle 4 faser, ved brug af resultater fra 4 arbejdspakker (A: application scenarios, B: Components and materials database, C: Round robin simulations, D: Knowledge base for decision makers).

Formidlingsmaterialer bliver tilgængelige på Task'ens hjemmeside: https://iea-es.org/task-39/, og viser:

A- hvad LTES er, hvordan de ser ud, hvad de anvendes til, nogle referencer og eksempler på LTES-projekter (use cases). Der er også blevet lavet en vejledning til LTES projektudvikling
B- et udkast til en database for materialer og komponenter brugt i LTES, samt en reference for nødvendig vandkvalitet. Databasen indeholder de informationer som er blevet undersøgt for forskellige LTES-teknologier, samt en vejledning til videreudvikling af databasen
C- hvordan man kan teste forskellige modelleringsværtøjer for alle 4 LTES-teknologier. En præcis vejledning til testmetoden er blevet udviklet, samt skabeloner til resultater, en liste over ledige modelleringsværktøjer og analysen/sammenligning af resultaterne fra den 1. fase beregninger
D- hvad er blevet lavet i løbet af projektet, gennem opdateringsmails, præsentationer under internationale konferencer og online webinars, samt en afslutningsworkshop, afholdt i December 2023

3. Project objectives

3.1 Objectives

The main objective of IEA-ES[1] Task 39 has been to develop reference information material on Large Thermal Energy Storages (LTES, see below for more details on the technologies in focus within the task) to prepare the acceleration of LTES implementation for District Heating (DH) and industry. This is performed by involving international experts of energy systems simulations, storage materials and storage constructions. Together, the experts contribute to preparing state-of-the-art guidelines as well as a list of references for all key phases of an LTES project, from idea to realization. Developed information material is tailored for key stakeholders of LTES projects, especially policy makers, authorities, and utilities to broaden the general knowledge on the studied technologies. Task 39 is a making the first thorough and accessible introduction of LTES technologies and associated tools for the relevant decision makers.

In detail, Task 39 aims at presenting the determining aspects of planning, design, decision-making and implementation of LTES for integration into DH systems and industrial processes, given the boundary conditions for different locations and different system configurations. The key objectives of the Task are the following:

- Definition of several representative application scenarios, the connected boundary conditions and Key Performance Indicators (KPIs);
- Improve LTES materials and materials performance measurement methods;
- Prepare guidelines for obtaining proper water quality;
- Compare the performance and accuracy of simulation models for LTES;
- Derive validation tests for LTES simulation models;
- Generate information packages for decision makers and actively disseminate the information;
- Organize a workshop for policy makers, in order to share LTES expertise with them and also discuss how to prepare the future of LTES.

3.2 Technology areas

Task 39 has had a focus on LTES technologies encountered in DH systems and projects, with an emphasis on giving examples of application scenarios, main implementation stages, modelling tools, materials development and water quality requirements. The focus was given to the thermal energy storages and not to the

[1] Energy Conservation and Energy Storage (ES) Technology Collaboration Program (TCP) of the International Energy Agency (IEA)

auxiliary equipment around it, although the context and boundary conditions in which LTES are implemented are described. The Task shares best practices for the following four LTES technologies:

- Tank Thermal Energy Storage (TTES), above ground and underground;
- Pit Thermal Energy Storage (PTES);
- Borehole Thermal Energy Storage (BTES);
- Aquifer Thermal Energy Storages (ATES).

Figure 1. “Sketch_4_LTES_Types.png”

PTES is a Danish specialty and most of the world’s large-scale PTES can be found in Denmark. Therefore, the expertise about this technology is brought by the Danish consortium, together with experience about LTES modelling tools, LTES materials and construction, and LTES reference concepts and application scenarios (especially connected to DH systems).

4. Project implementation

4.1 Evolution of the project

The project followed the initial plan set in the application, and evolved to establish more references than expected, as it was deemed necessary to fill the observed knowledge gap and lack of awareness that LTES have. The main objective of Task 39 was still achieved, and the evolution of the work came as an answer to the actual information need, as determined by during the course of the project.

Indeed, it was observed that many actors still don’t know the importance of LTES for renewable energy systems, the potential of such energy storages, where they can be used, and the main stages required to implement them. This observation is a direct consequence of the results from the questionnaire for decision makers of LTES made in WP D.

One example of the lack of knowledge about LTES technologies is the fact that many believe PTES to be a technology which can only be used as a seasonal Thermal Energy Storage (TES), although nothing about this technology limits it as such. This misconception comes from the fact that most implemented PTES have been used as seasonal TES in combination with Solar District Heating (SDH). So extra effort was put into explaining what LTES are, what they can do, what they look like, and so on.

The target groups of dissemination have also evolved, to be more focused on three specific groups:

- Policy makers and the general public;
- Project developers and project owners;
- Researchers and engineers.

Figure 2. “Diagram_LTES_project_stages.png”

Providing information material to these target groups is expected to have the biggest impact with regards to increasing the potential for LTES implementation. The reasons to focus on a different set of stakeholders is detailed in the next main section (in sub-section 5.2). The target groups[2] identified in the application phase of

[2] Utilities and energy companies, mainly with a technical perspective; Financial decision makers, mainly with an economic perspective; and Authorities (municipalities, energy agencies, politicians and other non-technical decision makers), with a combined technical, economic and environmental perspective

the project, however, have still been addressed by the developed information materials, and have been involved in the final workshop.

4.2 Achieved milestones

Most milestones were reached, during the period of the project. However, some milestones suffered from having a slow start, especially in WPs A and C. Moreover, in WP B, some of the expected data about materials could not be retrieved. The details about encountered issues for each WP is detailed below:

- In WP A, all milestones will be achieved by the end of January 2024. The delay can be explained by several facts:
  - the Subtask leader for WP A was only found in November 2021, slowing the start of the definition work which was necessary to move forward with the milestones;
  - it was unexpected that WP A would focus that much on project development and planning aspects, but it was deemed crucial, as there was an obvious lack of knowledge on this part (result of the information need gathering from WP D).
- In WP B, the structure for the database was established and described, but it remains incomplete by the end of the project. This is due to the fact that some materials test procedures, test results and materials data (initially expected to be made available by some of the manufacturers) were not shared, meaning that the materials database and test methodologies need to be completed with more data;
- In WP C, a special attention was given to describing a thorough set of modelling guidelines such that both the guidelines and the results are accessible after the work of Task 39. The test case description was finished for stage 1 calculations, in time for the calculations to be carried out, analysed and compared. Recommendations for modelling of LTES were also given in the process. One issue encountered is the long time that it took to get a list of all potential contributors and the models that they were planning to use. Another encountered issue is the time to get all contributors aligned on the test cases for the modelling comparison, which meant that stage 2 calculations could not be carried out during the time of the project;
- In WP D, the initial plan was to organize a physical workshop, but it turned out to be more complex than anticipated (organizing a physical workshop requires an event venue where many actors are available, a team to take care of practicalities, and none could be found before the end of the Task). Consequently, it was reevaluated and transformed into an online workshop to increase participation.

5. Project results

5.1 Achieved objectives and encountered obstacles

The main objective of the project was achieved, as reference information material about LTES has been developed by the Task. In all WPs, the main objective was reached, but some specific results could not be obtained:

- In WP B: it has been more difficult to collect data about materials from manufacturers than expected. In the application phase, manufacturers had announced they would share some data about their materials test results and testing procedures, but in the end, they decided not to, which made the database incomplete. However, a draft of the database as well as guidelines for materials testing and water quality for LTES has been reported and is ready for further development. The final report of WP B describes thoroughly the available data, the methodology to complete the database, and has created an organized structure for the database. It includes definitions of what can be called LTES components, subcomponents and materials;

- In WP C: the elaboration of model testing guidelines highlighted the lack of reference in terms of modelling comparison framework, and difficulties related to user-influence with regards to modelling work. It was therefore evaluated that extra effort would be put into making clear guidelines, including templates for inputs and outputs of simulation. The resulting guidelines constitute a testing reference for LTES modelling tools which will be made available online and open source, together with the results from all participants. These results constitute an extra outcome for Task 39. However, the elaboration of the guidelines took longer than expected, which made the first stage of calculations delayed. And although two stages of calculations were expected to be completed in the application phase of the project, in the end, only the first stage was.

5.2 Technological results and target groups

5.2.1 Definition of LTES, information need and main stages of LTES projects

Task 39 has defined LTES as:

- sensible (no phase change) TES;
- designed to store at least 1 GWh heat per year[3];
- at atmospheric pressure (no pressurized system);
- the stored heat should be suitable for discharge into DH Networks (DHN), at temperatures higher than 50°C.

In the early stages of the Task work, as a part of WP D, a questionnaire was sent out to the main target groups and various decision makers that could be involved with Task 39. This was done to gather the information need from decision makers and also create interest in the project: the actors answering the questionnaire were added to the mailing list of Task 39.

In total, 58 answers were gathered, from 14 countries, mostly from Germany, France, Denmark and the Netherlands, but also from China, Switzerland and Turkey. The type of stakeholders reached by the questionnaire were mostly utilities, academics and manufacturers. In total, 5 answers came from various levels of authorities and/or politicians (municipality, regional or national authorities, energy agencies). The highest expressed interest was directed towards PTES technology, with 36 responses out of 58, compared to 32 responses for ATES (multiple choices were allowed) and 28 responses for BTES.

The main information need expressed was techno-economic: highest interest was expressed towards investment costs, followed by operational KPIs such as storage efficiency, temperature range, and storage capacity. Then Operation and Maintenance (O&M) costs, main issues encountered with LTES and materials used. Then came design parameters such as economies of scale, sizing, system benefits and CO_2 reductions. Finally, planning aspects (such as the importance of quality insurance during construction) were rarely put forward by the different stakeholders, even though the planning process is a crucial part of LTES projects.

It was assessed that this lack of shown interest in planning aspects of LTES is due to a lack of knowledge, and therefore the group of experts from Task 39, together with the Subtask leader of WP A decided to put extra focus on describing the main stages of LTES projects to LTES project stakeholders. Today there are no guidelines for project developers and project owner to develop LTES projects, and those guidelines are necessary because there currently are no existing complete guides from idea to implementation about LTES. The main goal of WP A was then reformulated to:

- Present the basic information about LTES and define what can be considered an LTES;

[3] Households in Denmark consume on average 16 MWh/year for space heating and hot water in 2020 (source: Danish Energy Agency). Therefore, 1 GWh (1'000 MWh) is enough heat to supply the demand of 62 households for 1 year.

- Answer key questions about LTES (techno-economic parameters, O&M costs, materials used and design parameters, as expressed in the questionnaire answers);
- Identify, describe and share the main implementation stages of LTES projects;
- Identify and share clear KPIs which matter most for the different stages of LTES projects;
- Share best practices for good planning and implementation, as well as common challenges;
- Present the main advantages of LTES and their potential for sector coupling;
- Present all four technologies of LTES and use cases;
- Present techno-economic feasibility study involving different types of LTES.

In order to achieve those goals, results from previous international collaborations were used (HeatStore, Giga-TES, IEA-SHC[4] Task 55, CoolHeating, HeatRoadmap Europe, IEA-ES Task 35). Links to these projects are given at the end of the report in Section 8.3.

The main stages of all LTES were identified as:

- The opportunity, where the main objective is to identify the technical and economic potential for an LTES application within a given context. In this stage, information about the local context is gathered, a preliminary assessment of potential implementation sites and preliminary techno-economic calculations are made (see Figure 4);
- The design, which acts as a bridge between identifying opportunities and implementing such technologies in real-life applications. Its primary objective is to systematically address the potential barriers and mitigate the risks that might arise during the implementation phase, ensuring a smooth transition towards project execution, and establish specifications of the optimal LTES for a given context. In this stage, local constraints are further studied, techno-economic studies are carried out together with numerical approaches (see Figure 5);
- The tender, during which the general contractor or the different subcontractors are chosen based on a defined scope of work. Contracts need to correctly balance the role and responsibilities of each party to make the project ready to be financed;
- The implementation/operation stage, during which the LTES is built and connected to the district heating network. Subsequently, it is commissioned and operated for the duration of its planned lifetime, including service and maintenance.

[4] Solar Heating and Cooling (SHC) TCP of the IEA

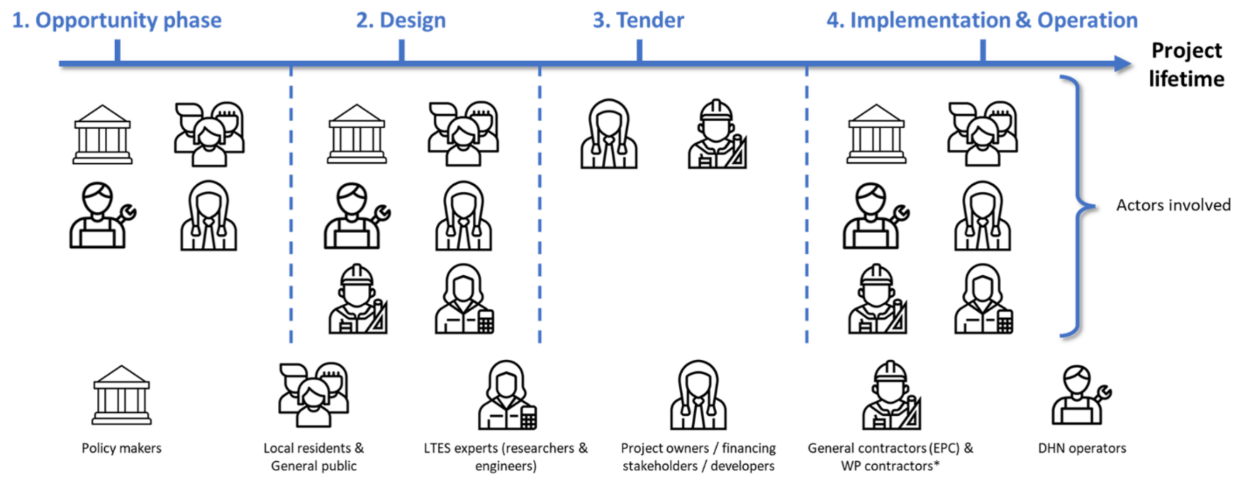

Figure 3. “Diagram_LTES_project_stages_detailed.png”

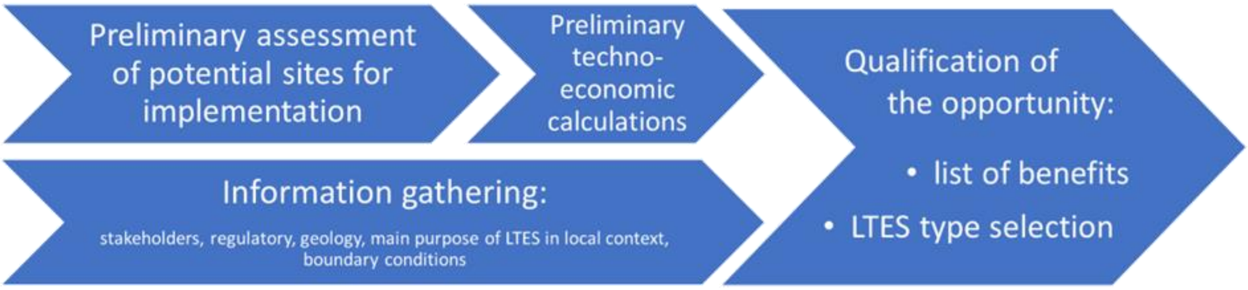

Figure 4. “Schematic_opportunity_phase.png”

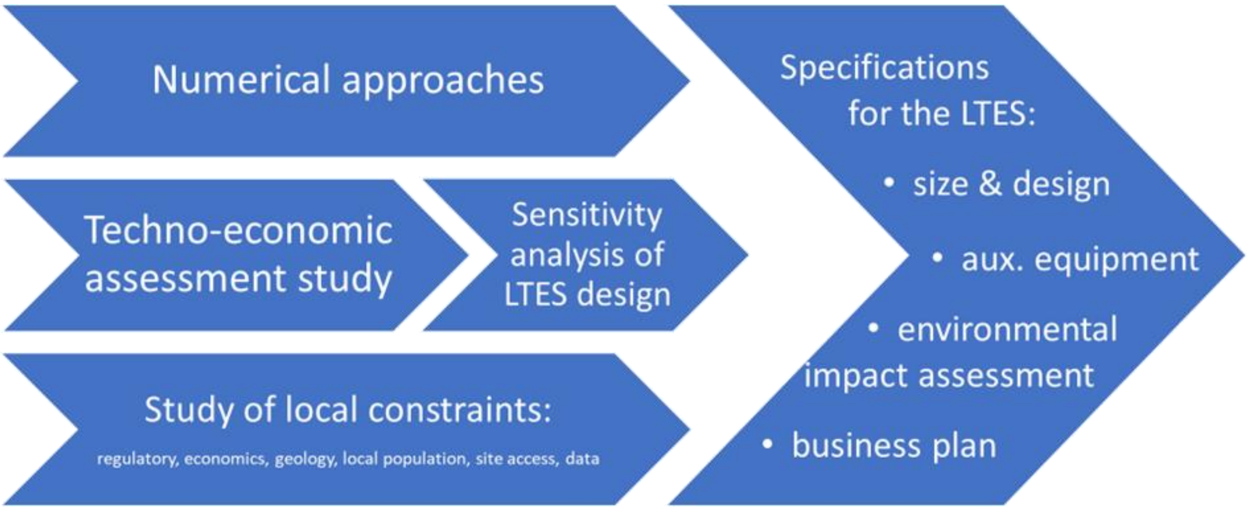

Figure 5. “Schematic_design_phase.png”

5.2.2 Target groups

The lack of knowledge from stakeholders of LTES about planning activities identified in the questionnaire activity of WP D has justified the need to change the main target groups for the information material elaborated in Task 39. The main target groups then become:

- Policy makers and the general public: this target group can include authorities such as politicians or municipalities, and local populations. These actors have an influence on the local and regional regulations, and should be well informed about LTES in order to increase the chances of acceptance of such technologies. Energy agencies are crucial mediators to reach out and disseminate to this target group. The information material prepared for this target group has the potential to be read by anyone wishing to learn more about LTES, such as the general public or financial actors. They benefit mostly from the information material developed in WP A;

- Project developers and project owners: they are the entities that will carry the LTES project and potentially own the LTES. This target group can be utilities, independent project owners or project developers, or municipalities. They benefit from the information material of all WPs;
- Researchers and engineers: they are the experts of LTES with regards to design, simulation, materials and R&D activities. This target group includes all technical actors, mainly researchers and engineers, but also contractors and manufacturers of LTES sub-components and materials. This is the main target group for the results of WPs B and C.

See Section 5.2.4 for details about the deliverables from Task 39. A table was made to explain which deliverables are relevant for which stakeholders.

5.2.3 Obtained results

5.2.3.1 Results from WP A: Application scenarios, assessment of concepts, integration aspects

In WP A, the first focus has been given to the introduction of general principles, and answer key questions such as:

- What kind of TES can be called ”LTES”?
- What is the competitor of LTES?
- Why are LTES needed for the energy transition?
- Where can LTES be found?
- What do LTES look like?
- What are the main implementation steps?

The other important part of the work of WP A has been to introduce the four LTES technologies and some illustrative use cases for each technology. For TTES, the chosen use case was the world’s largest TTES located in Berlin, Germany. The Danish consortium has actively participated in the definition work, the introduction of the technologies, and has given key inputs about PTES use cases for Dronninglund and Høje Taastrup, both in Denmark. For BTES, the use case provided by the experts from Task 39 is Emmaboda, in Sweden, and for ATES the use case of ECW / Ennatuurlijk Aardwarmte, located in the Netherlands.

Then, WP A has had a special emphasis on the main stages of LTES projects, KPIs and project implementation examples for all four types of LTES technologies[5]. The Danish consortium has given inputs about the PTES project in Dronninglund for this part.

An opportunity study of the different types of LTES in various meteorological regions of the United States of America (USA) was also reviewed by the consortium and included in the results from Task 39. This feasibility study presents an approach to a screening of LTES potential (applied to U.S. army buildings[6]). There are many ways to make techno-economic studies of LTES projects, and such studies often require the help of LTES experts. Task 39 provides the mains steps to follow in an opportunity study. The opportunity study in the USA is an illustration of what techno-economic calculations of the opportunity phase of LTES project can look like.

[5] Reports on these topics will be available on the IEA-ES Task 39 website in January 2024

[6] One of the partners within Task 39 provided a use case for LTES in various meteorological conditions, and was solved and reviewed by members of the Danish consortium of Task 39

Two extra contributions have been added to WP A, with active participation from the Danish consortium:

- A list of all known LTES projects[5], in order to gather in the same place all known references of implemented and upcoming LTES, for all four technologies;
- A report about the latest PTES implemented in Meldorf, Germany[5].

5.2.3.2 Results from WP B: Components and materials database

In WP B, the different system and component levels were defined, in order to clarify what is being studied and reported about LTES when speaking of a system, a component, materials, etc. This results in the pyramid structure presented in Figure 6, and contains 5 levels:

- Structure, which is the entire given LTES (such as a PTES or a BTES);
- Systems, which are parts of an LTES (such as the lid for a PTES or the roof for a TTES);
- Components, which are the different layers that constitute a system (such as the entire insulation layer of a PTES lid);
- Subcomponents, which are the individual physical elements constituting a component (such as an insulation panel used in a PTES or TTES insulation);
- Materials, which are the materials that constitute a subcomponent (such as stainless steel for the in-and-outlet pipes of an ATES).

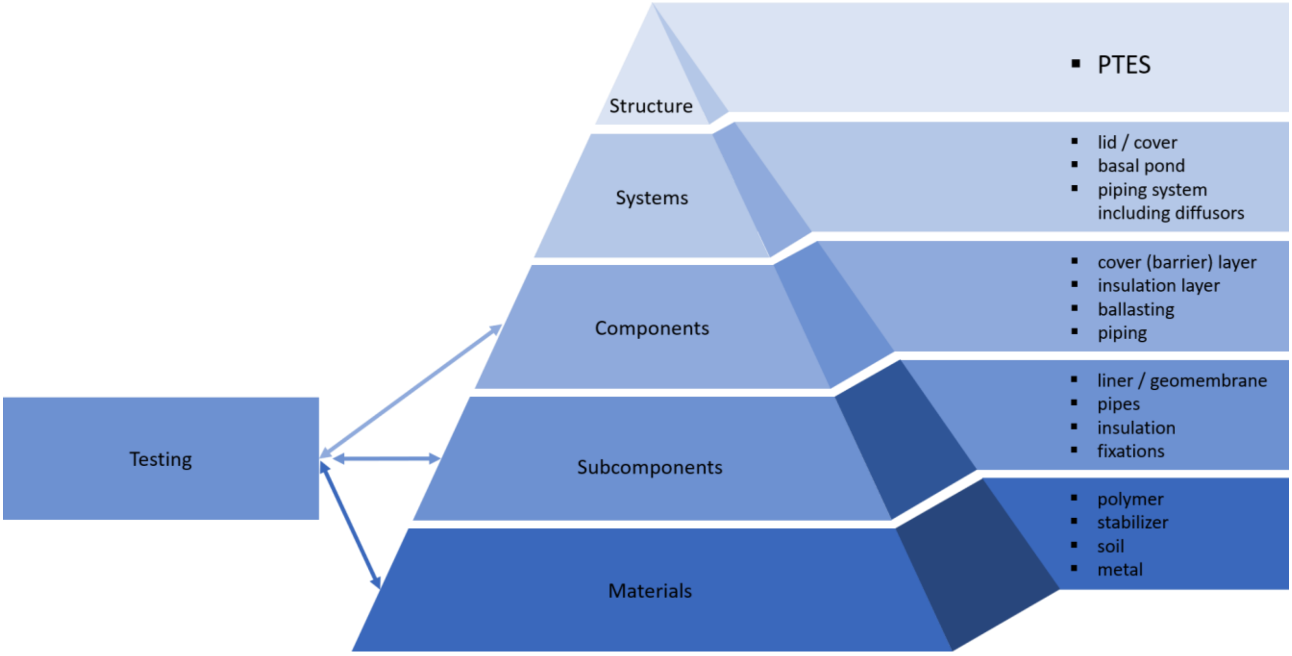

Figure 6. “Pyramid_Structure.png”

Then, a database structure was established and described, and data was gathered for different materials and sub-components, corresponding to the four LTES technologies. Guidelines to using the database were also made, in order to facilitate the choice of a material based on the function it should have. This is inspired by the procedure that should be followed to prepare the construction of an LTES. The database is not exhaustive and contains all the materials that were know and available to the experts of Task 39. Some of the data expected from manufacturers about specific LTES materials could not be obtained in the end. Although incomplete, this database provides a strong starting point for further development of knowledge on LTES materials, sub-components, components, and systems. It contains data (material properties and guidelines) about soil, insulation, pipes, geomembranes, and steel. This work has been done with the expertise of the Danish consortium in terms of materials and construction of LTES.

Another result of WP B is the gathering and analysis of water quality guidelines, which was done with PTES experience from the Danish consortium. Recommendations for water quality correspond to the standards set for water quality inside PTES to avoid corrosion of stainless steel inlets and outlets. Similar inputs were also given about water quality requirements for ATES from the other experts of Task 39.

With regards to materials testing, WP B has shared current best practices with regards to materials testing to determine the lifetime of some materials, sub-components, components, and systems. Papers describing the testing methodology have been gathered, and guidelines to the use of a lifetime assessment calculation tool has been made. This part of the work has been reviewed by the Danish consortium.

All of these results will be included in the final report of WP B[5].

5.2.3.3 Results from WP C: Round robin simulations

Within WP C, the first essential obtained result is the modelling guidelines for LTES simulation tools comparison. The chosen method for the comparison is round robin simulations, which is the comparison of different tools by giving them the same inputs (temperature profile, flowrates and geometry) and comparing the obtained outputs (energy balance, heat transfer and temperatures). The guidelines contain test case descriptions for the first stage of calculations, including templates for the inputs and outputs of the simulations, for all four technologies of LTES, and different configurations (see Figure 7):

- For TTES, two configurations have been studied, both of them with a cylinder geometry:
  - Above-ground TTES;
  - Underground TTES;
- For PTES, two configurations have been studied as well, both of them assuming a fully underground PTES:
  - A PTES shaped as an inverted truncated cone;
  - A PTES shaped as an inverted truncated pyramid;
- For BTES, only one configuration was given, with a cylindrical shape, and a fixed number of boreholes, borehole heat exchangers, as well as hydraulic connections of the boreholes;
- For ATES, only one configuration was given, with two wells.

Test case , phase 1 configuration label	TTES-1-UG	TTES-1-AG	PTES-1-C	PTES-1-P	ATES-1	BTES-1
Location	underground (UG)	above ground (AG)	underground	underground	underground	underground
Storage medium	water	water	water	water	soil-water	soil
TES rounded volume[3]	100,000 m³ water volume	50,000 m³ water volume	100,000 m³ water volume	100,000 m³ water volume	375,000 m³ soil volume (250,000 m³ pumped groundwater volume)	80,000 m³ soil volume
TES exact volume	100,961 m³ water volume	50,385 m³ water volume	99,404 m³ water volume	100,325 m³ water volume	373,253 m³ soil volume (only warm well side!)	80,646 m³ soil volume
Geometry (storage volume dimensions)	Cylinder H/D = 0.4 H = 27 m, D = 69 m	Cylinder[8] H/D = 1.0 H = 40 m, D = 40 m	Cone (C), (truncated, inverted) H = 16 m, wall slope: 1:2 (26.6°) D(top) = 119 m, d(bottom) = 55 m	Pyramid (P), (truncated, inverted) H = 16 m, wall slope: 1:2 (26.6°) D(top) = 109 m, d(bottom) = 45 m	2-well configuration depths: 200 m thickness aquifer-layer: 40 m, 160 – 200 m below ground surface R_T [4] = 54.5 m	Cylinder H/D = 1.8 H = 70 m, D = 38.3 m 128 BHE, BHE distance: 3 m, see also 7.1

H: Height; D: Diameter; H/D: Height-over-Diameter ratio; BHE: Borehole Heat Exchanger;

D(top): Diameter or edge length at the top of the PTES; d(bottom): Diameter or edge length at the bottom of the PTES

(3) Rounded values for labelling, reporting, dissemination etc. Exact geometry values shall be used for model configuration.

(4) Thermal radius $R_T = \sqrt{\frac{(C_w \cdot V_{inj})}{\pi \cdot H \cdot C}}$, with V_{inj}: injected water volume during one storage cycle in m³; C and C_W: volume-related specific heat capacities of aquifer and water in kJ/(m³.K); H: height of aquifer layer.

(8) The AG-tank is a non-pressurized flat-bottom tank. Any extra foundation is neglected, bottom thermal losses occur to the subsurface and not to the ambient air. Bottom thermal insulation does not extend horizontally beyond side walls. For simplification, no air gap between the water surface and the roof of the tank is considered.

Figure 7. “Test_case_description_extract_stage_1_configurations.png”

From those guidelines, stage 1 calculations were carried out by Task 39 experts, and an inventory of available modelling tools available for the four LTES technologies and their different configurations was made. For each model used for stage 1 calculations, a fact sheet was filled by the user/modeller, and these fact sheets are also shared as a result of WP C. The stage 1 calculations consist in applying a simplified yearly charging and discharging profile (also called “operating profile”) to the given LTES configuration: the profiles all have a charging period, an idle period where the LTES is left to rest, and then a discharge period. Energy balance, temperatures inside and around the LTES are compared for the different simulation models. Simulations should model 5 years of operations (for the TTES, PTES and BTES configurations) or 10 years of operations (for the ATES configuration) with a timestep of one hour maximum (see Figure 8 for an illustration of the yearly operating profiles).

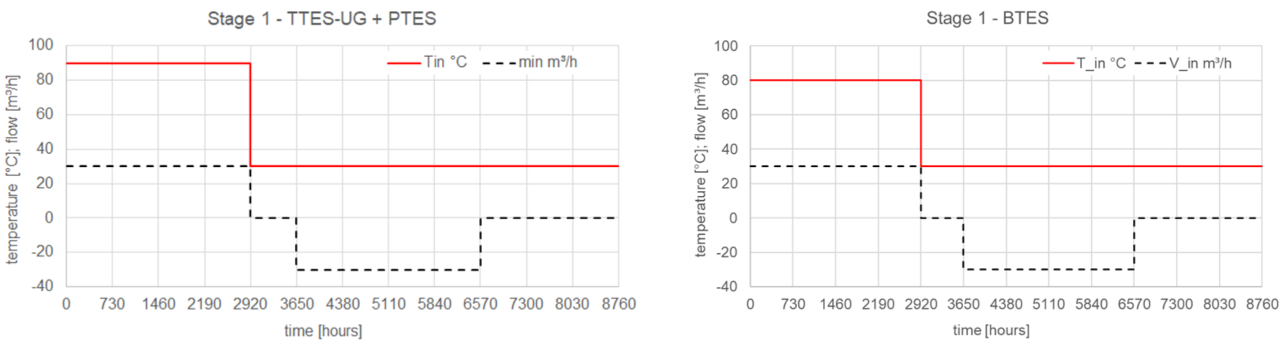

Figure 8. “Test_case_description_extract_stage_1_operating_profiles.png”

It was estimated, based on the knowledge and experience of Task 39 experts, that using monitoring data for round robin simulations would not improve the modelling comparison. Indeed, monitoring data usually contain gaps, lack precision (not adapted to short timesteps), and although these flaws can be corrected, having monitoring data as inputs doesn’t improve the comparison of modelling tools against each other (as round robin simulations do). Therefore, stage 2 calculations will also be based on theoretical charging and discharging profiles, which are representative of real operations of a LTES, but not based on monitoring data. As explained in the previous section, stage 2 calculations will not be a part of the results of Task 39 as originally planned, but have been prepared for the follow-up Task (see Section 7.2 for more information on the follow-up Task).

In addition to the available modelling tools, the result files from stage 1 calculations were also gathered and will be shared as an extra outcome of WP C[7].

The results from stage 1 calculations were analysed and compared, for all LTES configurations, and reported. The test cases for stage 1 calculations made it possible to analyse discrepancies between different models, and the variety of modelling tools used for the comparison made it possible to draw some conclusions on the reliability of the obtained results, and gave the opportunity to give recommendations for good practices with regards to modelling. What makes this analysis possible is the coherence of the results on various parameters: energy balance, temperatures in the water domain, temperatures in the soil domain, all of those during long simulation periods. Recommendations for modelling are also given in the test case descriptions.

The strong point of having such modelling guidelines and available open-source results, is that anyone can test their modelling tools against previously obtained results. The results comparison analysis provides a basis for comparing the different results, and the developed templates minimize the risk of having post-processing errors for the comparison. This complete approach (test cases, templates & results) is a first, applied to LTES.

The Danish consortium has been both active in defining the test cases, making the test case descriptions, and contributed with calculations for several cases, as well as with analysis and comparison of obtained results. The guidelines, the results and the comparison of the results will be included in the final report of WP C[5]. Moreover, the Danish consortium has published an article about the dataset for the monitoring done on the PTES in Dronninglund, together with the corresponding data from the first year of operation, in open-source.

5.2.3.4 Results from WP D: Knowledge base for decision makers

Besides from determining the information need, WP D has begun creating a general interest in LTES, by participating to several conferences and webinars. The Danish consortium introduced different technologies (PTES, TTES) and the work of Task 39 during various webinars:

- Presentation about the PTES in Høje Taastrup by PlanEnergi at the 15th IEA-ES TCP OnSeminar;
- General presentation of Task 39 by PlanEnergi, at the Enerstock conference online 2023 (session 4);
- Presentations by PlanEnergi (about TTES) and Aalborg CSP (about PTES) at the series of Webinars about the four technologies of LTES, organized by IF-Technology in 2023.

General interest in LTES was also created by sending update emails as well as making LinkedIn posts updating about the progress and activities of Task 39. The overall interest for LTES has been growing throughout the development of the Task, and positive feedback was received from the public at each conference or webinar. Direct communication was also established with the European Commission (E.C.)[8], the Austrian Ministry BMK[9], the Austrian climate and Energy fond, and energy agencies of several European Union member states: France, Denmark, Sweden and the Netherlands.

In terms of information material, the Task leaflet (called Task 39 brochure) was coordinated by WP D. It is published and available on the website of Task 39, and was made in two parts: an introduction, made for Policy Makers and the general public to get an overall presentation of LTES; and a use case leaflet, made for all actors, which contains a technology overview for all four types of LTES, together with details about at least one use case for each technology. As a part of the webinar series from IF-technology, WP D has also reviewed the factsheets about PTES and TTES technologies, that were inspired from the Task brochure.

In terms of dissemination, the Danish consortium has been active and represented in all Experts Meetings organized by Task 39. One of the experts meetings was hosted by Aalborg CSP in Aalborg, from September

[7] The results, not part of the initial plan of the work for WP C, will be made available in open-source in the beginning of 2024
[8] E.C. Directorate General for Energy
[9] Ministry of Climate Action, Environment, Energy, Mobility, Innovation and Technology

15th to September 16th 2022. The meeting included a site visit of the PTES in Dronninglund, which is equipped with a newly renovated lid.

Dissemination specifically to Danish actors has been made Danish district heating actors through the update email, and through a workshop organized by DBDH, where PlanEnergi presented the status of PTES technology development. Articles and further dissemination activities to share the results of Task 39 are planned in the beginning of 2024 (through DBDH and Dansk Fjernvarme).

Finally, WP D ended the Task with an online policy Workshop, “Are LTES a key element of the future energy system”, which aimed at establishing a discussion between experts of LTES, energy agencies and diverse Policy Makers. The workshop had two parts: a first part with presentations of the different actors represented, and a second part with the panel debate.

The first part of the workshop presented challenges, highlighted opportunities and showed best practices from the EU with regards to LTES implementation and policies. The objective of the second part, the panel debate, was to get inputs on what can be done to make LTES reach full potential, and what the next steps for the deployment of LTES are. The workshop had the following key findings:

- All speakers from the workshop agreed that LTES are key elements of the future energy system, and that they will help increase the share of renewable energies in heating and electricity networks;
- Moreover, the development of DH and cooling is an opportunity for the integration of more LTES;
- While there will be a demand for LTES, a key challenge for LTES experts and manufacturers is to make the technologies reliable and demonstrate their use in different contexts and countries;
- The active professionals with LTES currently constitutes a small community, and other actors should more actively be included in dissemination activities: district heating associations, smaller communities, cities and administrations;
- The conclusion of the workshop was that only a transdisciplinary approach will help LTES reach their full potential.

The workshop was recorded and is available online on the youtube channel of IEA-ES.

An extra deliverable from WP D is the update of the LTES monitoring data website varmelagerdata.dk and the corresponding English version heatstoragedata.eu. The websites contain information on the large-scale thermal storages in Denmark – in particular PTES. The six Danish PTES are all displayed on the frontpage map, and guidelines how to connect a storage system is also available.

The key activity of WP D has been to gather information materials prepared by Task 39, and the final deliverables are listed in Section 5.3 below.

5.2.4 List of deliverables and dissemination materials

In order to guide potential readers, a table was made for each main target group of Task 39 (see Section 5.2.2). The guide can be found in Figure 9.

Which Task 39 deliverables should I read?

For Policy makers & the general public:

- High interest deliverables:

Work Package	Deliverable name	Deliverable type
A	Task brochure - Introduction	Online & physical leaflet
A	Method to carry an LTES project - Important questions and KPIs - Synthesis	Synthetic report
A	LTES project development case studies	Synthetic report
A	List of LTES projects	List
A	PTES Use Case - Meldorf	Online leaflet
D	Policy workshop - Are LTES a key element of the future energy system?	Workshop
D	LTES live and historical monitoring data	Note & website URLs

- Interesting deliverables:

Work Package	Deliverable name	Deliverable type
A	Task brochure - Use Cases	Online & physical leaflet
A	Analysis of LTES application for public/military communities located in different climate zones	Report
A	Subtask A main report: Method to carry an LTES project - Main stages, case studies and KPIs	Report
A	PTES project development case study - Meldorf	Report
C	Numerical models list - Overview and collection of model fact sheets	Report
C	Modelling guidelines - Round robin test case description	Report
C	Results of stage 1 round robin test case simulations - Analysis	Report

Stakeholder description:
- **Policy makers & general public**: authorities (politicians or municipalities) and local populations. Have an influence on the local and regional regulations. The deliverables for these stakeholders has the potential to be read by anyone wishing to learn more about LTES, such as the general public or financial actors. Mainly interested by deliverables developed in work package A

For Project developers, project owners & financing stakeholders:

- High interest deliverables:

Work Package	Deliverable name	Deliverable type
A	Task brochure - Introduction	Online & physical leaflet
A	Task brochure - Use Cases	Online & physical leaflet
A	Method to carry an LTES project - Important questions and KPIs - Synthesis	Synthetic report
A	LTES project development case studies	Synthetic report
A	Analysis of LTES application for public/military communities located in different climate zones	Report
A	Subtask A main report: Method to carry an LTES project - Main stages, case studies and KPIs	Report
A	List of LTES projects	List
A	PTES Use Case - Meldorf	Online leaflet
A	PTES project development case study - Meldorf	Report
B	Subtask B main report: Components and Materials Database	Report
C	Numerical models list - Overview and collection of model fact sheets	Report
C	Results of stage 1 round robin test case simulations - Analysis	Report
D	Policy workshop - Are LTES a key element of the future energy system?	Workshop
D	LTES live and historical monitoring data	Note & website URLs

- Interesting deliverables:

Work Package	Deliverable name	Deliverable type
C	Numerical models list - Model fact sheet template & naming convention	Template
C	Modelling guidelines - Round robin test case description	Report
C	Modelling guidelines - Load profiles	Template
C	Modelling guidelines - Results template	Template
C	Results of stage 1 round robin test case simulations - Result files	Filled templates

Stakeholder description:
- **Project developers, project owners & financing stakeholders**: entities that will carry the LTES project and potentially own the LTES. Can be utilities, independent project owners or project developers, municipalities, or investors. Potentially interested by deliverable from all work packages

For Researchers & engineers:

- High interest deliverables:

Work Package	Deliverable name	Deliverable type
A	Task brochure - Use Cases	Online & physical leaflet
A	Analysis of LTES application for public/military communities located in different climate zones	Report
A	List of LTES projects	List
A	PTES Use Case - Meldorf	Online leaflet
A	PTES project development case study - Meldorf	Report
B	Subtask B main report: Components and Materials Database	Report
C	Numerical models list - Overview and collection of model fact sheets	Report
C	Numerical models list - Model fact sheet template & naming convention	Template
C	Modelling guidelines - Round robin test case description	Report
C	Modelling guidelines - Load profiles	Template
C	Modelling guidelines - Results template	Template
C	Results of stage 1 round robin test case simulations - Analysis	Report
C	Results of stage 1 round robin test case simulations - Result files	Filled templates
D	LTES live and historical monitoring data	Note & website URLs

- Interesting deliverables:

Work Package	Deliverable name	Deliverable type
A	Task brochure - Introduction	Online & physical leaflet
A	Method to carry an LTES project - Important questions and KPIs - Synthesis	Synthetic report
A	LTES project development case studies	Synthetic report
A	Subtask A main report: Method to carry an LTES project - Main stages, case studies and KPIs	Report
D	Policy workshop - Are LTES a key element of the future energy system?	Workshop

Stakeholder description:
- **Researchers & engineers**: experts of LTES with regards to design, simulation, materials and R&D activities. Includes all technical actors, mainly researchers and engineers, but also contractors and manufacturers of LTES sub-components and materials. Mainly interested by deliverables developed in work packages B & C

Figure 9. “Guide_for_task39_deliverables.png”

A list of all deliverables, including the deliverable number (which was used in the naming convention for the files uploaded on the website), was also made available and can be found in Figure 10.

List of Task 39 deliverables

Deliverable nr.	Work Package	Deliverable name	Deliverable type
A0a	A	Task brochure - Introduction	Online & physical leaflet
A0b	A	Task brochure - Use Cases	Online & physical leaflet
A1	A	Method to carry an LTES project - Important questions and KPIs - Synthesis	Synthetic report
A2	A	LTES project development case studies	Synthetic report
A3	A	Analysis of LTES application for public/military communities located in different climate zones	Report
A4	A	Subtask A main report: Method to carry an LTES project - Main stages, case studies and KPIs	Report
A5	A	List of LTES projects	List
A7a	A	PTES Use Case - Meldorf	Online leaflet
A7b	A	PTES project development case study - Meldorf	Report
B	B	Subtask B main report: Components and Materials Database	Report
C1a	C	Numerical models list - Overview and collection of model fact sheets	Report
C1b	C	Numerical models list - Model fact sheet template & naming convention	Template
C2a	C	Modelling guidelines - Round robin test case description	Report
C2c	C	Modelling guidelines - Results template	Template
C3a	C	Results of stage 1 round robin test case simulations - Analysis	Report
C3b	C	Results of stage 1 round robin test case simulations - Result files	Filled templates
D1	D	Policy workshop - Are LTES a key element of the future energy system?	Workshop
D2	D	LTES live and historical monitoring data	Note & website URLs

Figure 10. “List_of_task39_deliverables.png”

5.3 Dissemination of results

The following sections describe the different publications and dissemination efforts that were made by the Danish consortium in connection with Task 39.

5.3.1 International dissemination

5.3.1.1 Peer-reviewed articles

In the course of the work for Task 39, three peer-reviewed articles were published:

- One peer-reviewed article as conference contribution to “Geosynthetics: Leading the Way to a Resilient Planet” was co-authored by PlanEnergi, and is about liner materials used for PTES technologies (published in 2023). It was presented at the 12th ICG International Conference on Geosynthetics in Rome, Italy;
- One peer-reviewed article in “Solar Energy” was written by DTU and co-authored by PlanEnergi, about the monitoring dataset from the PTES in Dronninglund (published in 2023);
- One peer-reviewed article in “Applied Thermal Engineering” was written by DTU, about heat losses in PTES when there is groundwater flow in the soil surrounding the storage (published in 2023).

5.3.1.2 Articles published in professional magazines and journals

In the course of the work for Task 39, three articles were published in specialized magazines and journals:

- One article in EuroHeat&Power (EHP) Magazine, co-authored by PlanEnergi, about the PTES in Høje Taastrup (in German);
- Two articles in nachhaltige technologien, respectively written and co-authored by PlanEnergi:
    - The first one was published in the edition of February 2021 entitled “Groß wärmespeicher”, focused on LTES, and retraces the historical development of PTES in Denmark (in German);
    - The second article was published in the edition of February 2023 entitled “Energiewende für Städte und Gemeinden” and provides an update on the work from Task 39 as well as information about the PTES in Høje Taastrup (in German).

5.3.1.3 International conference contributions

In the course of the work for Task 39, four contributions were made at the following international conferences:

- PlanEnergi presented Task 39 and participated to a panel debate in session 1.7b “Decarbonising Europe's Heating and Cooling” at the Energy Storage Global Conference - ESGC 2022, held in Brussels, Belgium. Direct contact was also established with the E.C., Directorate General for Energy;
- PlanEnergi presented flexible DH from Denmark and talked about LTES at the International Sustainable Energy Conference – ISEC 2022 in Graz, Austria;
- DTU made a presentation about the first results from the PTES in Høje Taastrup at the Solar World Congress 2023, held in New Dehli, India;
- Presentation about the potential of using landfill areas for PTES implementation by PlanEnergi, October 18th & 19th 2023 in Karlsruhe, Germany.

5.3.1.4 Organization of workshops

- PlanEnergi has organized the online policy workshop on December 5th, 2023, with the help of DTU during the workshop for the moderation of the participants. 120 people had subscribed to the event and about 80 people were present online for the workshop;

5.3.1.5 Other international dissemination

The project results have been disseminated internationally through the following channels:

- Update emails and LinkedIn posts, shared by the group of experts of Task 39 and to the IEA-ES TCP ExCo delegates. These posts have the potential to reach over 200 people directly by mail, and many distribution networks through LinkedIn and other networks accessible through the Task 39 experts;
- Webinars, see Section 5.2.3.4;
- Task 39’s website;
- IEA-ES experts meetings, gathering all organizations involved in the work of Task 39.

Further dissemination of Task 39 results is planned in the beginning of 2024 through Euroheat & Power’s newsletter, the distribution of a last update email and a LinkedIn post.

5.3.2 National dissemination (in Denmark)

5.3.2.1 Participation to workshops and other Danish events

Dissemination to Danish actors was done by participating to several conferences and events:

- Participation to meetings within the thermal energy storage and system integration working groups of DACES (Danish Center for Energy Storage). The members of DACES are, amongst others, Danish research institutes and technology manufacturers within energy storage, as well as other companies interested in energy storage. Sharing progress of Task 39 with these groups ensures dissemination to active Danish stakeholders;
- A general presentation about PTES and TTES and Danish activities within IEA-ES TCPs was made by PlanEnergi at the annual meeting of the Danish Board of District Heating (DBDH) in Assens. The meeting also included a panel debate about which TES solutions have potential for which applications, and PTES as well as TTES were put forward as key elements of the future for DH. This event was the occasion to reach out to Danish utilities, municipalities, and consultancy companies active within DH, and therefore interested in LTES.

5.3.2.2 Other national dissemination

National dissemination was also ensured by sharing directly to Danish actors through the distribution of update emails, directly by email (mailing list) or through LinkedIn. The mailing list of Task 39 contains Danish trade organizations, consulting companies, energy utilities, and other decision makers such as project developers, the Danish energy agency, municipalities, district heating associations and research institutes.

Further dissemination of Task 39 results is planned in the beginning of 2024 through an article published in DBDH's magazine "HotCool", and with a webinar organized with Dansk Fjernvarme.

6. Utilisation of project results

6.1 Utilisation of project results

The results from the work carried out in Task 39 are meant to be used as a global reference about LTES, which covers an introduction to the technologies of LTES, the 4 main phases of an LTES development project, as well as best practices in terms of available modelling tools and comparison methodology, material properties and testing, water quality, as well as implementation of all technologies of LTES.

The results are primarily aimed at giving information to the 3 main target groups (see Section 5.2.2), but can potentially be used by all stakeholders of LTES (see Figure 9).

6.2 Contribution to energy policy objectives

Task 39 has developed reference information about LTES for high-level stakeholders by:

- Introducing the topic with accessible information material (such as the Task 39 brochure, see Section 5.2.3.4);
- Sharing concrete examples of LTES;
- Engaging the discussion between policy makers and experts of LTES (see the Task 39 workshop).

The results from the more technical work packages (WP B and C) have made accessible the state-of-the-art methodologies for LTES modelling and LTES materials development. This Task has also presented references for project development, from feasibility to implementation, together with use cases for each technology of LTES. The work therefore covers the whole value chain of LTES implementation.

This work has confirmed that LTES are a key element of more sustainable and resilient energy systems and will facilitate the acceleration of the uptake of LTES by making accessible technical, economic and planning aspects of LTES project development. Having more LTES, means more sector coupling, more renewable energies in DHC, more efficient use of primary energy resources, contributing to energy policy objectives and the decarbonisation of the energy system in the current green transition context.

6.3 Associated PhD work

The results of this project were utilized by Ioannis Sifnaios as part of his PhD studies at the Technical University of Denmark (DTU). Specifically, project results were incorporated in lectures given at DTU related to LTES systems. Additionally, results were presented to researchers and experts working with storage at the Solar World Congress, organized by the International Solar Energy Society. The work of this PhD aimed at answering key technical questions about PTES that hadn't been addressed by literature until now and have the potential to be widely used by new researchers, engineers and consultants working with LTES. The project results were published as open-access articles in scientific journals, which facilitates accessibility of the work.

7. Project conclusion and perspective

7.1 Conclusions of Task 39

Task 39 has gathered most experts and actors of the energy and construction sectors that had knowledge about LTES, in Europe and worldwide, and has concluded that to make LTES reach their full potential, it is now necessary to reach out to other actors such as district heating associations, municipalities and regions, and international energy agencies worldwide. Only with a transdisciplinary approach will it be possible accelerate the uptake of LTES. Reaching out to other actors will spread awareness around LTES technologies and enable a better coordination of all stakeholders of LTES. If politicians, local communities, and municipalities are aware of the potential of LTES to help decarbonise the energy sector, they will likely be in favour of the deployment of corresponding technologies. It is also the occasion to get associated to the foreseen growth of DHC networks, which require significant volumes of thermal storage to include more renewables.

Given the high implementation pace required to reach energy policy goals, it will also be fundamental to coordinate with the industrial sector but also policy makers, to make sure technology providers can follow an increasing demand for LTES and have the necessary qualified workforce available to implement a significant amount of LTES systems. There are options for funding already available in many EU countries for the deployment of technologies coupled to DHC, but qualified workers to build such infrastructures may be lacking in the upcoming years. Knowledge about the planning and implementation stages of LTES is also crucial for stakeholder and decision makers to have in mind for the proper deployment of LTES, and Task 39 has made specific information available to cover this aspect.

The workshops carried out during Task 39 have brought up the question of reliability of LTES technologies as a determining factor for the intake of LTES. Danish PTES are a world-know reference for the technology, but the first generation of large-scale PTES have all known some issues, during implementation and operations, and it is important to show that these references can be used to improve future designs of the technology, make them robust, efficient and long-lasting, while keeping low investment costs.

Task 39 has therefore concluded that demonstration of the technology and robustness of the LTES structures will be another crucial step to accelerate the intake of LTES technologies. Failure to do so will prevent LTES from being used as a key, large-scale energy storage, providing flexibility to the energy system of the future, at an accessible cost. In this context, Denmark can keep its competitive advantage acquired in the development of the PTES technology and will be a key expert of the TREASURE project (see Section 7.2 for more information about this demonstration project).

All in all, Task 39 has paved the way for the acceleration of LTES intake and highlighted the upcoming challenges to deploy the cheapest[10] form of large-scale (GWh and above) renewable energy storages.

7.2 Perspectives and future work

7.2.1 Follow-up Task

In November 2023, the follow-up Task “Accelerating the uptake of Large Thermal Energy Storages” of Task 39 and has been approved and has received the number 45 from the Executive Committee (ExCo) of IEA-ES. IEA-ES Task 45 is starting on January 1st, 2024, and have a duration of 4 years.

In Task 45, several activities will be carried out:

[10] Cheapest in terms of total costs of ownership, including means of energy production

- Continuation of the work from Task 39 on LTES materials database and materials test methods;
- Continuation of the modelling work: stage 2 calculations and development of simplified pre-design tools for LTES system integration;
- Development of construction and performance check standards for LTES;
- Inventory of improved LTES concepts, recommendations for the vast deployment of LTES and dissemination to broader audiences.

The technology scope is broadened to LTES technologies achieving 120°C.

7.2.2 E.C. HORIZON demonstration projects

From the consortium of Task 39, several partners gathered in two separate consortiums that were awarded funding from the E.C.'s HORIZON program (call HORIZON-CL5-2023-D3-01-14 "Demonstration of innovative, large-scale, seasonal heat and/or cooling storage technologies for decarbonisation and security of supply"):

- TREASURE, which is focused on the demonstration of PTES. The project includes 7 demonstrator projects, 15 satellite initiatives, and one monitoring/reference project (the PTES from Høje-Taastrup). Wim van Helden, from AEE INTEC, Austria, is the project coordinator (same person as the Task 39 manager);
- USES4HEAT, which is focused on the demonstration of BTES and ATES. The project includes two demonstrator projects connected to DHN. Silvia Trevisan, from KTH, Sweden, is project coordinator.

With these two demonstration projects, the opportunity is given to demonstrate that the full-scale LTES technologies described in Task 39 are reliable, cost-efficient, and replicable in different contexts and countries.

8. Appendices

8.1 Forkortelsestabel/Table of abbreviations:

Herunder findes tabellen hvor alle forkortelser som bruges i rapporten er samlet / Hereunder there is a table gathering all the abbreviations used in the report:

International Energy Agency	IEA
International Energy Agency – Energy Storage	IEA-ES
Technology Collaboration Program(s)	TCP(s)
Executive Committee	ExCo
IEA-ES Task 39	Task 39
European Commission	E.C.
Thermal Energy Storage(s)	TES
Large Thermal Energy Storage(s)	LTES
Tank Thermal Energy Storage(s)	TTES
Pit Thermal Energy Storage(s)	PTES
Borehole Thermal Energy Storage(s)	BTES
Aquifer Thermal Energy Storages(s)	ATES
District Heating	DH
District Heating Networks	DHN
District Heating and Cooling	DHC
Solar District Heating	SDH
Key Performance Indicators	KPIs
Work Package(s)	WP(s)
Operation and Maintenance	O&M
Danish Board of District Heating	DBDH
Danish Center for Energy Storage	DACES
Technical University of Denmark	DTU
EuroHeat&Power	EHP

8.2 Links to annual reports

In the project period, three IEA-ES TCP annual reports have been published:

- IEA-ES TCP – Annual report 2020
- IEA-ES TCP – Annual report 2021
- IEA-ES TCP – Annual report 2022

8.3 Links to other relevant information material

8.3.1 Peer-reviewed articles

- Polyolefinic geosynthetics as key components in future energy systems – A case study and perspective; Wetzel H., Peham, L., Sørensen P.A., Wallner, G.M.; Conference Proceedings, Geosynthetics: Leading the Way to a Resilient Planet, 2023
- Dronninglund water pit thermal energy storage dataset; Sifnaios I., Gauthier G., Trier D., Fan J., Jensen A.R.; Solar Energy, 2023
- Heat losses in water pit thermal energy storage systems in the presence of groundwater; Sifnaios I., Jensen A.R., Furbo S., Fan J.; Applied Thermal Engineering, 2023

8.3.2 Articles in professional magazines

- Erdbeckenwärmespeicher im Großraum Kopenhagen als Kurzzeitwärmespeicher im Einsatz, Wetzel, H., Bruus F., EH&P Magazine 09/2023
- Entwicklung von Erdbecken-Wärmespeichern in Dänemark, Sørensen, P. A., nachhaltige tech-nologien 02/2021
- Große thermische Wärmespeicher – Von der grünen Wiese bis zur Integration in Städte, Sørensen, P. A., Moser, M., Van Helden, W., nachhaltige technologien 02/2023

8.3.3 Conference contributions

- Energy flexible District Heating; Gauthier, G.; International Sustainable Energy Conference – ISEC 2022
- IEA-ES Task 39 - Large thermal energy storages for district heating; Gauthier, G.; Energy Storage Global Conference - ESGC 2022
- Experiences from the first short-term pit thermal energy storage; Sifnaios I., Jensen A.R.; Solar World Congress 2023[11]
- Erdbeckenwärmespeicher zur Potenzialoptimierung von Deponieabwärme und ungenutzter Deponief-lächen; Seume M., Sünnwoldt M., Wetzel H.; Seminarband 44 zur Deponie und Altlasten

8.3.4 Workshops

- IEA-ES Task 39 Workshop: Are Large Thermal Energy Storages a Key Element of the Future Energy System
- Erfaringer og økonomi med forskellige typer varmelagre - Introduktion til varmelagring og forbindelsen til sektor kobling; Gauthier, G.; DBDH medlemsmøde, Assens, 6. December 2023[12]

8.3.5 Webinars

- Pit Thermal Energy Storage in Høje Taastrup - Case study of a first-of-its-kind weekly thermal storage; Gauthier, G., 2023, 15th IEA-ES TCP OnSeminar
- IEA-ES Task 39 - Large thermal energy storages for district heating; Gauthier, G., 2023, Enerstock con-ference online
- Series of Webinars about LTES organized by IF-Technology in 2023

8.3.6 References to external work about LTES

- HeatStore: project focused on underground thermal energy storages, showcasing best practices of PTES and BTES in Denmark, but also of ATES. This project has been used in many instances for the work of Task 39, especially for finding KPIs and LTES reference projects;
- GigaTES: project looking into the further development of existing LTES technologies, using PTES and TTES as starting points. This project has been used as a reference for best practices of project develop-ment, materials testing and modelling (see the final report of GigaTES project). As a part of this project, a modelling tools comparison was carried out, and has inspired the corresponding work in Task 39. Some results from the modelling tools comparison were published in 2021 and co-authored by members of Task 39. The paper was presented at the International Renewable Energy Storage Conference 2021 (IRES 2021):
    - Comprehensive Comparison of Different Models for Large-Scale Thermal Energy Storage, in: Pro-ceedings of the International Renewable Energy Storage Conference 2021 (IRES 2021); Ochs, F.,

[11] The proceedings of the conference are not published online yet
[12] The presentation, partly in Danish, wasn't made available online by DBDH yet

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- IEA-SHC Task 55 - Towards the Integration of Large SHC Systems into DHC Networks: project focusing on the integration of large solar thermal systems into DHC networks, including means of thermal storage. This reference project has developed very high-quality infographics, and has been largely used as inspiration in Task 39;
- CoolHeating: project has promoted the implementation of "small modular renewable heating and cooling grids" for communities in South-Eastern Europe. This project also had some interesting material with regards to introduction to DHC, best practices, and means of thermal storage;
- IEA-ES Task 35 – Flexible Sector Coupling: this IEA-ES Task has looked at energy storage for sector coupling, and amongst other things the importance of TES for DH networks. Some of the results from this Task were used in Task 39 to show the potential for LTES in connection with DH;
- Heat Roadmap Europe: project developing low-carbon heating and cooling strategies, called Heat Roadmaps, by quantifying and implementing changes at the national level for 14 EU Member States, which together account for approximately 85-90% of total heating and cooling in Europe. This project has promoted DHC as a solution to decarbonize the heating and cooling sectors, and put forward the use of both short term and seasonal TES.