Technology Collaboration Programme
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IEA Technology Collaboration Programme

International Energy Agency

Technology Collaboration Programme on Energy Storage

(ES TCP)

Task 39

Large Thermal Energy Storages for District Heating

Executive Summary

Submitted for and approved by

the 98th ES TCP ExCo meeting, 12-15 November 2024, Richland, USA.

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CONTENT

LIST OF ABBREVIATIONS

ATES	Aquifer Thermal Energy Storage
BTES	Borehole Thermal Energy Storage
DH	District Heating
DHN	District Heating Network
E.C.	European Commission
ES	Energy Storage
IEA	International Energy Agency
KDP	Key Design Parameter
KPI	Key Performance Indicator
LTES	Large Thermal Energy Storage
O&M	Operation and Maintenance
PTES	Pit Thermal Energy Storage
R&D&I	Research and Development and Innovation
ST	Subtask
TTES	Tank Thermal Energy Storage
TTS	Thermal Storage Structure

KEY MESSAGES AND POLICY RECOMMENDATIONS

Large Thermal Energy Storages are key components to enable fully renewable heat supply in district heating systems and allow larger penetration of renewable electricity in electricity grids. Decision makers, policy makers, district heating companies, financing partners, municipalities, engineers and industries should have sufficient information, suited tools and efficient processes to accomplish the timely realisation of the required LTES systems. LTES also play a crucial role in the overall energy system, as a key enabler of sector coupling, energy independency, and are essential for the large-scale and long duration storage of energy, both at a local and (inter)national scale.

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. National and international support is needed for demonstration and innovation projects with which to gain experience and establish improvements.

A collection of key performance indicators is available to help in the decision-making process for LTES integration. Economic, social and financial indicators need further development, and the LTES community should be strengthened with experts from these fields.

Numerical simulation software is available to determine the performance of LTES as a component. The optimisation of district heating systems with integrated LTES components still needs user-friendly, fast, and accessible design and pre-design tools of LTES technologies.

The costs of LTES systems still can be reduced. To reach lower costs, material, component and process development is needed. This can be best achieved with national but foremost international support for R&D&I projects. To compete with cheap fossil fuels, LTES systems also need to be seen as an integrating part of a decarbonized heating and cooling system, and as such should be supported by appropriate regulation.

MAIN RESULTS IN A NUTSHELL

Main results

The experts in Task 39 worked to determine the aspects that are important in planning, decision making, and realising large thermal energy storages for the integration into district heating and to cast the findings in different forms of dissemination.

The main results are:

A definition of Large TES: a sensible storage that charges/discharges at least 1 GWh of heat per annum, independent of the number of cycles.

A comprehensive list of Key Performance Indicators, either technical, economic, or environmental, or for different LTES technologies, or for a single storage, a storage system or a storage integrated into a DH system.

Information leaflets about the LTES technologies and about typical use cases.

A list of worldwide realised LTES projects.

A document with guidelines for LTES project development, broken down into the phases Opportunity, Design, Tender and Implementation & Operation.

A structure for a materials database, to be further implemented and filled with data on materials and components of LTES technologies.

Description of a lifetime estimation procedure for polymeric materials for pit thermal energy storages.

Guidelines for the water quality to guarantee long lifetimes of LTES components.

An inventory for LTES numerical simulation models including model fact sheets with key information on single models.

A set of six test cases for the verification of LTES simulation tools for four LTES technologies, including detailed test case results for various simulation models and a comparative evaluation showing good agreement between the tools.

A good overview of the LTES information needs of the different stakeholders in LTES planning, building and operating.

A Task39 website with information material and results.

Main recommendations

The main recommendations, resulting from the work and discussions between Task 39 experts and from the conference, webinars and workshop discussions are:

LTES are key elements of the future energy system, and they will help increase the share of renewable energies in heating and electricity networks.

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 constitute a small community, and other actors should more actively be included in dissemination activities: district heating associations, smaller communities, cities and administrations.

Only a transdisciplinary approach will help LTES reach their full potential. Therefore, the group of experts should be broadened with experts from economics, finance, communications, sociology, et cetera. Alternatively, the group can seek active collaboration with other expert groups, for instance other Tasks within the IEA.

The comparison between LTES simulation models should be further enhanced, with charging and discharging patterns that are resembling practical applications.

There is a need for numerical modelling tools that are fast and accurate, enabling a faster system simulation and optimisation of LTES integrated into District Heating and Cooling or other large heating and cooling systems.

There is a need for more detailed material and component data that are publicly shared through the materials database.

There is a strong need for practical data on material ageing and deterioration and for theoretical models with which material lifetime can be estimated.

These recommendations have formed the basis for the work in the follow-up of Task39: Task 45 “Accelerating the Uptake of Large Thermal Energy Storages”. The Task started 1 January 2024 and will run for 4 years.

EXECUTIVE SUMMARY

1 Short Description of Task 39

1.1 Objectives and Scope

Task 39 was aimed at determining the aspects that are important in planning, designing, decision-making and realising LTES for the integration into district heating systems and industrial processes, given the boundary conditions for different locations and different system configurations.

The key objectives of the Task were:

- Definition of several representative application scenarios, the connected boundary conditions and key performance indicators
- Improve LTES materials and materials performance measurement methods
- Prepare guidelines for obtaining proper water qualities
- 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

1.2 Organisational Structure

The Task was organised around 4 Subtasks.

Subtask A worked on application scenarios, the definition of key performance indicators (KPI), the assessment of storage concepts in the scenarios and the detailing of integration aspects. Subtask B was aimed at composing a database of suitable materials that can be used for LTES. Subtask C was dedicated to a round robin of the numerical simulation of LTES with real validation data sets.
Subtask D had the goal to develop and distribute information packages for decision makers.

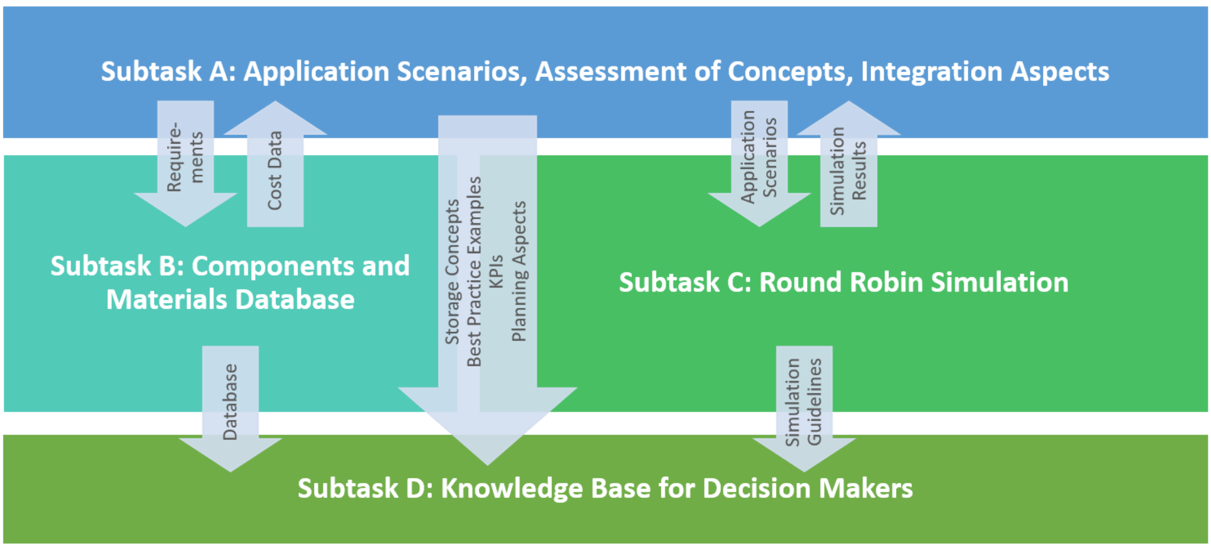

Figure 1: *Schematic representation of the Task breakdown into Subtasks and the information flow between the Subtasks*

1.3 Duration of Task

Task 39 had a duration of 3 years. It started 1 January 2021 and ended 31 December 2023.

1.4 Experts Meetings

The activities, progress and planning were discussed at semi-annual expert meetings. Due to the corona pandemic, the first meetings were held online only. Later meetings were in person, with parts hybrid.

The table below lists the expert meetings' city, country, dates and number of participants.

City	Country	Date	# Participants
Online	-	27 Oct and 3 Nov 2020	27
Online	-	10 and 11 May 2021	33
Online	-	2 and 3 November, 2021	34
Graz	Austria	8 April 2022	24
Aalborg	Denmark	15 and 16 September 2022	24
Hamburg	Germany	23 and 24 May 2023	24
Graz	Austria	26 and 27 September 2023	17

1.5 Participation

The table below lists the institutions that participated in the work of Task39. On average, 69 experts from 11 countries contributed.

Institutions	Country
AEE INTEC, UIBK, AIT, JKU, SOLID, AGRU	Austria
PlanEnergi, DTU, Ramboll, Aalborg CSP, Bobach Solutions	Denmark
Chalmers University, Absolicon, MuoviTech AB	Sweden
SOLITES, siz energie+, TH Ulm, Solmax, AGFW, Vattenfall, Stadtwerke München, g-quadrat	Germany
NRCan	Canada
newHeat, CEA	France
CREAR-UniFI, RSE	Italy
Groene Warmte, IF technology	The Netherlands
Cukurova University, Gazi University	Turkey
Nottingham Trent University, University of Birmingham	United Kingdom
TESS	United States

2 Summary of Subtasks

2.1 Subtask A: Application Scenarios, Assessment of Concepts, Integration Aspects

The aim of this subtask was to provide to LTES main stakeholders such as project developers a sound basis of materials to pursue a LTES project from an opportunity to implementation.

2.1.1 LTES final definition

To set the perimeter of the work in Task 39, a first step has been to set a definition for LTES. The agreed definition in the scope of this Task is the following:

"LTES are sensible Thermal Energy Storages designed to store at least 1 GWh heat per year at atmospheric pressure. The stored heat should be suitable for discharge into District Heating Networks, at temperatures higher than 50°C."

The storages which are considered in this Task are TTES, PTES, BTES and ATES, which fit the previous criteria. The perimeter of the storage can include a post-heating unit such as a heat pump for BTES to fit the criteria for example.

2.1.2 Assessing LTES performance thanks to KPIs

Key performance indicators (KPIs) are necessary at every stage of an LTES project to evaluate all its aspects. There are many different indicators that can be used to conduct the activities mentioned previously. A comprehensive list of KPIs has been created and examples cases have been presented to illustrate their use.

KPI LIST

A KPI list has been created and sets a first reference to assess the performances of those type of storage. It aims at being exhaustive regarding technical, economic and environmental aspects.

The listed KPIs are introduced with their formula, unit, their use and a reference. Moreover, they are sorted in different categories:

- Their type: technical, economic or environmental.
- The storages they apply to: TTES, PTES, BTES and/or ATES.
- The scope of this KPI: storage alone, storage system or the whole DHN (cf. Figure 2).
- The project stage when this KPI should be calculated: opportunity, design or operation.
- The main target group: policy makers, project owners/developers or researchers/engineers.

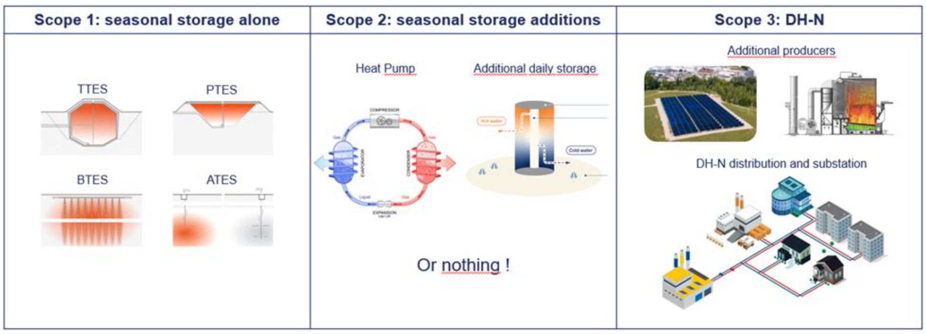

Figure 2: Scopes considered for indicators boundaries

This list can be used as a reference for various actors of LTES projects to be able to analyze the behavior of a LTES through their point of view. An extract of this list with the major KPIs is available in the main report of the subtask. The full list is obtainable upon request and will be further elaborated in the upcoming Task 45.

EXAMPLE CASE OF KPI USE FOR TYPICAL LTES APPLICATIONS

To complete the list that has been created, example cases were presented in deliverable A4 to illustrate the use of several of the main KPIs. Internal studies conducted by Newheat with their internal modelling tools, including TTES and PTES were then described to illustrate the interpretation of the KPIs. On the one hand they can be used to quantify the influence of different operating conditions (control strategy and annual variations of heat availability and demand) on the performance of the storage system and thus allow the optimization of operating strategies. On the other hand, KPIs enable the definition of a performance guarantee based on the model simulation results, showing the influence of design parameters on the heat delivered from the LTES.

This work illustrated the importance of test procedures which will be tackled in Task 45, to ensure a common standard for each KPI calculation.

2.1.3 LTES project list

A list of existing LTES projects has been elaborated in order to gather all references at the same location and provide a database for future project developers who would like to get a glimpse at previous experiences.

This list is available online on a SharePoint hosted by PlanEnergi, and is available for addition or edition, by filling a form whose result will pe processed by the host.

Country	Storage type	Location/name	Storage duration	Application/purpose	Storage medium	Volume [m3]	Status	Year commisionned
Canada	BTES	Drake Landing (Ok	Seasonal	Seasonal storage of solar heat, fo	Soil	33.700	Operational	2006
China	PTES	Tibet Langkazi	Weekly	Seasonal/weekly storage of solar	Water	15.000	Operational	2018
Czech	BTES	Paskov			Soil			2011
Denmark	HT-ATES	Hørsholm			Water		Decommision	1982
Denmark	PTES	Marstal 1	Seasonal	Seasonal storage of solar heat	Water	10.000	Decommision	2003
Denmark	PTES	Marstal 2	Seasonal	Seasonal storage of solar heat	Water	75.000	Operational	2012
Denmark	BTES	Braedstrup	Seasonal	Seasonal storage of solar heat	Soil	19.000	Operational	2012
Denmark	PTES	Dronninglund	Seasonal	Seasonal storage of solar heat	Water	60.000	Operational	2013
Denmark	PTES	Gram	Seasonal	Seasonal storage of solar heat	Water	122.000	Operational	2014
Denmark	PTES	Vojens	Seasonal	Seasonal storage of solar heat	Water	203.000	Operational	2015
Denmark	PTES	Tøftlund	Seasonal	Seasonal storage of solar heat	Water	85.000	Operational	2017
Denmark	PTES	Høje Taastrup	Weekly		Water	70.000	Under	2023
Denmark	TTES	Copenhagen	Hourly/daily	Store heat from electric boiler & H	Water	22.000	Announced	2025
Denmark	TTES	Silkeborg	Weekly		Water	4*16'000	Operational	2017
Denmark	TTES	Aalborg	Multifunctio		Water			

Figure 3: Extract of the LTES list available on Task 39 website

2.1.4 Method to carry an LTES project

Finally, a major part of the work in Subtask A was to provide guidelines for LTES project development to guide the different stakeholders in their understanding and role throughout an LTES project. The proceeding was split in two parts within the STA main report. First, a standard process development was introduced including the main activities, challenges and tools. Secondly, actual project developments were depicted parallel to the project development process, to give real-life examples on the activities and challenges introduced in the first part.

First, the development of an LTES project is split between 4 stages introduced in the following figure. This report being aimed at the project's stakeholders, they are categorized into each stage, to understand quickly their focus

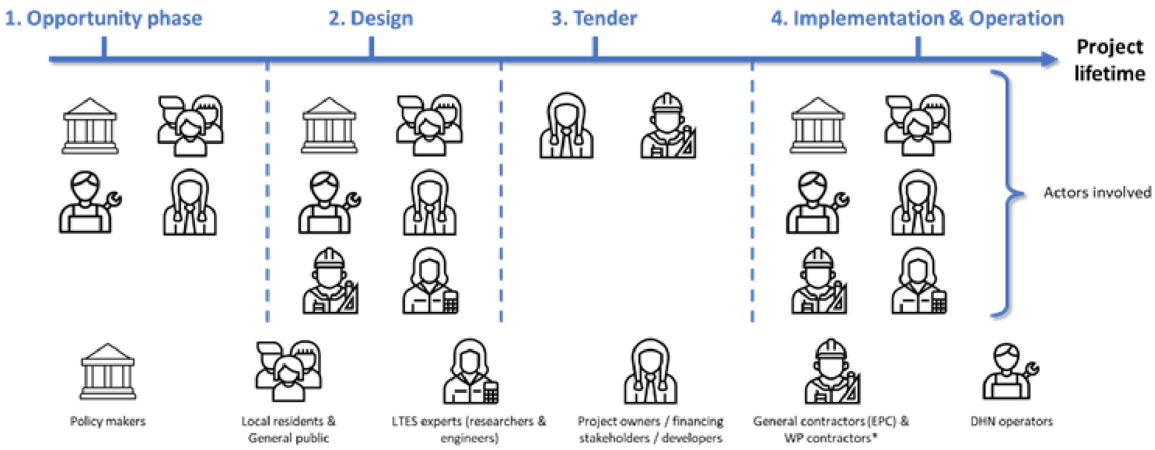

Figure 4: Stages of an LTES project and actors involved

This report is available both as a synthetic version, in [deliverable A1](#) and as a more detailed report in the main report of the subtask. For each stage described in the previous figure, the report details its main objectives, activities, common challenges, tools, and most used indicators. Those main topics provide a global view of the return of experience from existing projects and the keys to develop new ones. For more details, see the ST A [main report](#).

2.1.5 Case studies: application to existing LTES project

This deliverable ([A2](#)) serves as an illustration of the deliverable presented in the previous part with real-life project development examples.

1 project was selected for each technology:

- Berlin 56'000 m^3 TTES for district heating owned by Vattenfall and commissioned in 2023
- Dronninglund 60'000 m^3 PTES owned by Dronninglund district heating and commissioned in 2014
- Emmaboda 140 boreholes BTES owned by Xylem Water Solutions AB and commissioned in 2010
- Middenmeer 440'000 m^3 ATES owned by Ennatuurlijk Aardwarmte and commissioned in 2021

The project developers were asked to provide feedback regarding their experience in their project regarding the following topics:

- Modelling and sizing
- Storage materials
- Land
- Permitting process
- Contractual scheme
- Tendering process
- Construction
- Operation & maintenance

Altogether with deliverable A1, a global picture regarding project development is provided to each potential actor involved, with synthetic and detailed material to reach a broad public.

2.2 Subtask B: Components and Materials Database

Materials and component properties are essential for planning, designing, and performance assessment of any thermal energy storage system. The performance of each component/material is directly coupled to the lifetime and cost/benefit analyses of a thermal storage structure. Materials in a thermal storage structure are exposed to higher temperature and moisture levels than the ambient condition. Thus, it is essential to have reliable and accurate material data.

Objectives of Subtask B were creating a material database, guidelines for proper water quality, recommendations for corrosion protection, and proposing novel hygrothermal and mechanical test methods. However, the topic 'Proposal for novel hygrothermal and mechanical test methods' was not treated. A few test methods were compiled. In general, the follow-up task (Task45) will take up the progress described in this report to further improve the level of detail for each objective.

Creating a database and guidelines for all types of thermal storage was a challenge. Thus, the group members tried to give more general guidelines that were valid for almost all technologies, and in some cases, they were more specific for one technology.

2.2.1 Material and Component Data

A status of available materials was gathered and listed. With the help of schematic drawings of each storage type, a principal visualization of their composition is intended. Initially, the gathered material and component data considered the PTES technology. A considerable choice of materials has been gathered, of which for nearly most materials a comment section has been filled to reveal closer information, often collected by experience from projects. Furthermore, the common materials from PTS technology by other technologies were transferred to the part of the database related to those technologies. Finally, the database for the technologies is completed with relevant material proprieties for the specific storage technology.

2.2.2 Database

Establishing a database aims to provide up-to-date accurate information on LTES materials and components. The design process consists of different steps, which include i) defining the purpose of the database, ii) finding and organizing the information into tables, iii) selecting the information to be included in each table, and iv) establishing the relationship between them.

The database will be hosted on the 'Supergen Energy Storage Network' (https://supergenstorage.org/), an energy storage platform that supports the energy storage community joining (experts) and disseminating (knowledge) through academia, industry, and policy. The Supergen Energy Storage Network+ website is linked to, https://ukesto.supergenstorage.org, where UK energy storage facilities and databases are showcased. A beta version of the database is available; however, it is not public yet.

2.2.3 Measurement Methods Lifetime Estimation

The lifetime of the materials and components is crucial for the economic feasibility of all thermal storage technologies. Measuring the lifetime characterization of materials in real-time and scale is time-consuming. Generally, acceleration of measurement and minimization of the sample size are used. A test and assessment method for liner polymeric materials, based on miniaturized specimens was implemented at the Institute of Polymeric Materials and Testing by the University of Linz, AT. Special attention was given to the acceleration of the aging mechanisms by elevated temperature and specimen miniaturization. A method based on cumulative damages was used. The lifetime assessment is based on a) simulated temperature loading profiles for LTES, and b) extrapolated experimental aging data on the micro-specimen level. These data were weighted and accumulated considering a cumulative damage model.

2.2.4 Guidelines for proper water quality and procedures for obtaining this water quality

The water is used as the heat transfer fluid in the district heating network and at a storage medium, e.g. in PTES. The challenges related to water quality in a district heating network are very similar to a thermal storage structure (TSS). Thus, existing knowledge in the district heating field and experiences from PTES were used.

The water in a TES should have a sufficient quality to fulfil the following functions i.e. avoid or minimize corrosion in metallic-based components, avoid bacteria growth in the storage, avoid harmful influence on the service life of the polymer and other materials for a LTES.

The water in a TSS could be circulated in an open or closed system. In an open system, the water is in contact with atmospheric air. Thus, oxygen cannot be kept out of the water, and it will increase the risk of corrosion damage. The water temperature in a TSS is between 5°C and 95°C.

2.2.5 Guidelines/recommendations for corrosion protection

Corrosion protection is relevant for all metal parts in direct contact with the TES storage medium and heat transfer fluid. That is diffusers, pipes, heat exchangers, pumps, and valves. In this context, the heat transfer fluid is always water with some degree of treatment as discussed above. The necessary precautions to avoid corrosion are highly connected to the level of water treatment and the ability to keep the water quality in a controlled state. The guidelines and recommendations for corrosion protection are based on experience from traditional DH systems and experience from existing LTES.

For TTES (tank storage) made of steel, the oxygen level in the water can be kept at a minimum and the recommendations for DH systems (pipe network) can be used.

For open system storage like PTES, oxygen in the water cannot be avoided. A variety of approaches to corrosion protection have been realized in PTES projects until now. The experience from some of these projects is described in the guideline (Requirements for water quality in pit thermal energy storages, Bobach, 2022).

2.3 Subtask C: Round robin simulation

For the proper design and system integration of large thermal energy storages (LTES), suitable, accurate and verified simulation models are essential. Various models were developed in the past for different LTES concepts (see Table 1), simulation platforms and application purposes.

Important aspects in an LTES project development are, e.g., the LTES dimensioning that can only be carried out considering the LTES system integration. Suitable models for this must consider the short-term interaction with the system's energy producers and sources as well as energy consumers. Models for this purpose have been mostly developed for system simulation platforms like TRNSYS or Modelica/Dymola. Another important aspect is the detailed component-level design and optimisation of an LTES. For this task, models in more detailed and flexible simulation tools like COMSOL Multiphysics are used.

Table 1: Overview of LTES simulation models used by Task 39 partners

<table>
<tr><th>Purpose / Storage type</th><th colspan="2">System simulation</th><th>TES design optimization</th></tr>
<tr><td>ATES</td><td colspan="2">TRNSYS:
Type 345 TRNAST
Type 1380</td><td>FEFLOW
MODFLOW
HST2D/3D</td></tr>
<tr><td>BTES</td><td>TRNSYS:
Type 346 SBM , Type 370
Type 557 DST, Type 1373</td><td>Modelica:
MoSDH library
– BTES model</td><td>COMSOL Multiphysics
ANSYS FLUENT
FEFLOW</td></tr>
<tr><td>PTES</td><td>TRNSYS:
Type 343 (cone), Type 1322 (pyramid)
Types 1535/1301 (cone), UGSTS
MATLAB Simulink:
Matlab Large-Scale TES</td><td>Modelica:
Dymola Dis PlaTES
LargeTESmtk
– PTES model
MoSDH library
– PTES model</td><td rowspan="2">COMSOL Multiphysics
ANSYS FLUENT
OpenFOAM</td></tr>
<tr><td>TTES</td><td>TRNSYS:
Type 340 (above ground)
Type 342 (buried and above-ground)
Types 534/708 (ground buried)
Type 1534 (above ground)
Types 1534/1302 (ground buried)</td><td>Modelica:
Dymola Dis PlaTES
LargeTESmtk
– TTES model
MoSDH library
– TTES model
MATLAB Simulink:
Matlab Large-Scale TES</td></tr>
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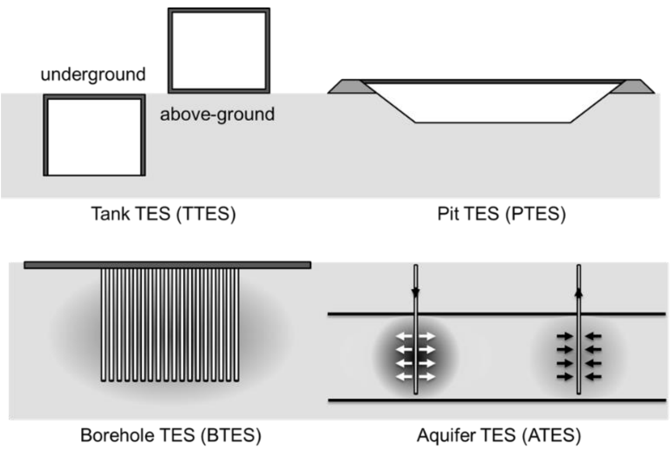

Figure 5: Overview of LTES concepts considered in the comparative simulations.

The aim of Subtask C work was to develop and apply a verification method for LTES simulation models.

2.3.1 Methodology

Verification of simulation models can be done in different ways. Commonly used approaches include comparing simulation results with measurement data or analytical solutions, or comparing simulation results between different, ideally partially already validated simulation models. Because of the high complexity and dynamic operation conditions, analytical solutions are only available for single or very simplified heat transfer aspects. Also, high-quality measurement data is difficult to find for LTES, as real-scale laboratory experiments are not available and monitoring systems of realised projects are designed for operational and not scientific purposes. Completeness and quality of measurement data can, therefore, not satisfy scientific requirements in most cases. For these reasons, a verification procedure based on pre-defined and representative test cases and comparative simulations was developed. More specifically, (1) test cases for the LTES concepts shown above have been defined, (2) simulation models for the test cases were created and applied by the subtask participants, and (3) the simulation results of the models were compared. As some of the models have been validated before, a comparison of model results can be a valid way for verification, if deviations between the concerned model results are acceptable.

Table 2 gives an overview of the test cases defined for the comparative simulations. For each test case, a detailed description of the specific storage configuration and the required simulation outputs was developed. These test case descriptions are available in one of the subtasks deliverables, see below.

Table 2: Overview of test cases defined for the verification of LTES simulation models (CH: charging, DC: discharging, BHE: borehole heat exchanger).

Test case	**ATES-1**	**BTES-1**	**PTES-1-C**	**PTES-1-P**	**TTES-1-AG**	**TTES-1-UG**
Description	ATES two wells	BTES cylindrical	PTES truncated and inver-ted cone	PTES truncated and inver-ted pyramid	TTES above-ground	TTES under-ground
TES volume	375 000 m³ (soil)	80 000 m³ (soil)	100 000 m³ (water)	100 000 m³ (water)	50 000 m³ (water)	100 000 m³ (water)
Storage medium	soil-water	soil	water	water	water	water
Insulation	-	top	top	top	top, side, bottom	top
CH/DC devices	two wells	128 BHE	top & bottom diffusors	top & bottom diffusors	top & bottom diffusors	top & bottom diffusors

Simple yearly operation profiles for the test cases were defined at this stage. A charging period of four months was assumed with constant mass flow and constant inlet temperatures, followed by a one-month idle phase. After this, a four-month discharging period (again with constant mass flows and inlet temperatures), followed by a three-month idle phase. The simulation period for the test cases was five years. However, for the ATES-1 test case, ten years were used. The multi-year simulation periods were used to also consider the heat-up phase of the surrounding ground, which mainly takes place in the first years of operation.

Besides the LTES configurations and the operation profiles, a set of model outputs was defined for each test case to enable a clear and efficient assessment of simulation outputs. The pre-defined outputs comprise the most important energy flows, temperatures and mass flows of the hydraulic circuits for charging and discharging of the LTES, as well as temperature developments in the storage volumes and in specific locations of the surrounding ground. For the pre-defined model outputs an evaluation template is also available. Table 3 provides an overview of the main parameters for the definition of the test cases.

Table 3: Parameters for the definition of test cases.

• **LTES configuration, e.g.**
  • geometry
  • well configuration
  • borehole heat exchanger configuration (BHE)
  • hydraulic devices / connections for charging and discharging
  • insulation
• **Thermophysical properties**
  • water
  • insulation material
  • ground properties
	• **Numerical parameters**
	  • discretisation
	  • far field boundaries
	  • simulation period and time step
	• **Boundary conditions**
	  • initial conditions
	  • operational profiles
	• **Model outputs**
	  • flows and temperatures of hydraulic circuits
	  • heat flows
	  • temperature sensor positions:
	    • inside the storage volume
	    • in the surrounding ground

2.3.2 Conclusions and Outlook

In general, the results for all test cases show good agreement between the participating models for the major energy values, such as the charged and discharged amounts of heat on a yearly or monthly basis. The short-term (hourly) temperature development in the storage volume and the TES outlet temperature towards the system also show satisfactory agreement but with somewhat higher deviations in some cases. Temperature results for the defined locations in the surrounding ground also show somewhat higher deviations in some cases; however, post-processing of model outputs, e.g., interpolation between single cells of the numerical grid, can be both time-consuming and error prone.

The discussions between the task members during the development and definition of the test cases and during the simulation phase showed that, even though all members are experts in the field of LTES, there were still some misunderstandings and misinterpretations of specific details in the early stages, which led to differences in simulation results that could be eliminated after some clarifications. This emphasizes the crucial need for detailed and clear definitions for comparative simulations to make sure that differences in results are caused by the investigated models and not by user behaviour.

Table 4 gives an overview of the deliverables available from Subtask C.

Table 4: Subtask C deliverables.

Deliverable	Type of deliverable
Overview and descriptions of LTES simulation models	Report
C1: Collection of model fact sheets	
Description of test cases	
C2a: Description of Test Cases for Comparative Simulations	Report
C2b: Load profiles for test cases	MS Excel-File
C2c: Result template for test cases	MS Excel-File
Results of comparative simulations	
C3a: Results of comparative simulations	Report / reference book
C3b: Result files from participating models / partners	MS Excel-Files

These documents and files allow other interested users to apply the presented test cases for their own models and verify or compare their results with the results from this work.

In the follow-up IEA ES Task 45, the work will be continued with additional and more advanced test cases that will consider more dynamic and realistic operational profiles as well as sensitivity studies for the most important design parameters.

2.4 Subtask D: Knowledge base for decision makers

2.4.1 Objectives & activities

The main objective of Subtask D has been to broaden the knowledge and increase the awareness of LTES and to inform relevant decision makers and stakeholders about the benefits and possible obstacles. The overall aim of the task has been redefined as to "provide tools, references and methods to guide stakeholders of LTES projects". 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 of different locations and different system configurations.

2.4.2 Results

The main achievement of IEA-ES Task 39 is the reference information material on LTES to prepare the acceleration of LTES implementation for District Heating (DH) and industry. This material been developed by involving international experts of energy systems simulations, storage materials and storage constructions. Together, the experts have contributed 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. The 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 has made the first thorough and accessible introduction of LTES technologies and associated tools for the relevant decision makers.

2.4.2.1 Determination of information need and target groups

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

The survey gathered answers 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 utilities, academics, manufacturers as well as various levels of authorities and/or politicians (municipality, regional or national authorities, energy agencies).

The highest expressed interest was directed towards PTES technology, followed by ATES and then BTES. The main information need expressed in the questionnaire answers was techno-economic, 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, and finally, planning aspects (such as the importance of quality assurance during construction) were rarely put forward by the different stakeholders.

This lack of shown interest in planning aspects of LTES being due to a lack of knowledge, it was 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 ST A was then reformulated to include project development aspects of LTES within the task.

The main target groups for the dissemination and information material were then also redefined to the three following:

- Policy makers and the public (authorities such as politicians, energy agencies or municipalities, and local populations).
- Project developers and project owners (utilities, independent project owners or project developers, or municipalities).
- Researchers and engineers (experts of LTES with regards to design, simulation, materials and R&D activities).

The identification of the main stages of LTES project development has been an important outcome of Subtask A. These stages are used in the diagram in Figure 4 as a reference in the LTES project lifetime to show which main actor/target group is involved during which stage, and which information material from Task 39 is relevant for these stages. Each information material has an associated work package.

2.4.2.2 List of deliverables and information material

The deliverables prepared and gathered by Subtask D are summed up in the extended final report.

All the deliverables are available on the Task 39 website. A figure to give an overview of the available deliverables and a guide to the main target groups was made and published on the Task 39 website as well.

Besides from the deliverables of Task 39, extra information material was developed by the experts of the working group, and have also been made available on the website of Task 39:

- Presentations of IEA-ES Task 39 given at various conferences and workshops in 2022
- An article published in Nachhaltige Technologien in February 2023
- A webinar series organized by IF Technology, RVO and TKI Urban Energy in November and December 2023. The webinar series has been recorded and made available online, together with the presentations and factsheets about the 4 LTES technologies studied in Task 39

2.4.3 Dissemination activities

2.4.3.1 Update emails, posts and presentations

One of the main activities of Subtask D has been to create a general interest in LTES, by participating to several conferences and webinars. The Task 39 consortium introduced different technologies (PTES, TTES) and the work of Task 39 during various external webinars and conferences. See the lists of these in the final report.

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.)[1], the Austrian Ministry BMK[2], 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 ST D. It is published and available on the website of Task 39, and makes a general introduction to LTES, as well as the different technologies of LTES, with at least one use case for each technology..

Dissemination specifically aimed at national actors was done by the different Task 39 actors, for example in Denmark, Austria, Germany and the Netherlands.

2.4.3.2 Policy workshop

Finally, Subtask D ended the work of Task 39 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 a panel debate.

The workshop ended with key conclusions, which are relevant for policy recommendations and are included in the following section. It was also recorded and is available online on the youtube channel of IEA-ES.

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[1] E.C. Directorate General for Energy

[2] Ministry of Climate Action, Environment, Energy, Mobility, Innovation and Technology

3 Comprehensive Results and Recommendations for Deployment

The experts in Task 39 worked to determine the aspects that are important in planning, decision making, and realising large thermal energy storages for the integration into district heating and to cast the findings in different forms of dissemination.

The main results are:

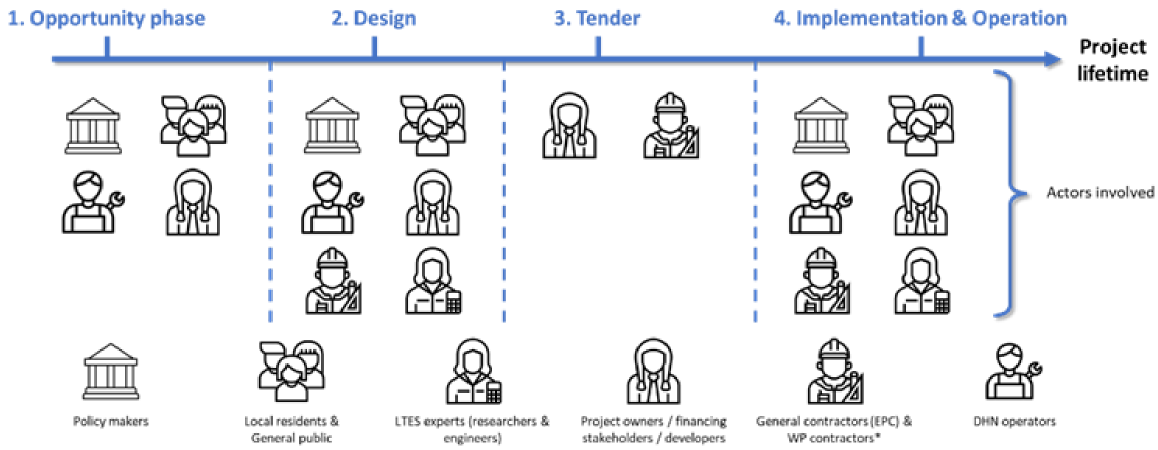
A definition of Large TES: a sensible storage that charges/discharges at least 1 GWh of heat per annum, independent of the number of cycles.

A comprehensive list of Key Performance Indicators, either technical, economic, or environmental, or for different LTES technologies, or for a single storage, a storage system or a storage integrated into a DH system.

Information leaflets about the LTES technologies and about typical use cases.

A list of worldwide realised LTES projects.

A document with guidelines for LTES project development, broken down into the phases Opportunity, Design, Tender and Implementation & Operation.



A structure for a materials database, to be further implemented and filled with data on materials and components of LTES technologies.

Description of a lifetime estimation procedure for polymeric materials for pit thermal energy storages.

Guidelines for the water quality to guarantee long lifetimes of LTES components.

An inventory for LTES numerical simulation models including model fact sheets with key information on single models.

A set of six test cases for the verification of LTES simulation tools for four LTES technologies, including detailed test case results for various simulation models and a comparative evaluation showing good agreement between the tools.

A good overview of the LTES information needs of the different stakeholders in LTES planning, building and operating.

A Task39 website with information material and results.

The main recommendations, resulting from the work and discussions between Task 39 experts and from the conference, webinars and workshop discussions are:

LTES are key elements of the future energy system, and they will help increase the share of renewable energies in heating and electricity networks.

LTES are also a key enabler of sector coupling and energy independency, and are essential for the large-scale and long duration storage of energy, both at a local, national, and international scale.

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 constitute a small community, and other actors should more actively be included in dissemination activities: district heating associations, smaller communities, cities and administrations.

Only a transdisciplinary approach will help LTES reach their full potential. Therefore, the group of experts should be broadened with experts from economics, finance, communications, sociology, et cetera. Alternatively, the group can seek active collaboration with other expert groups, for instance other Tasks within the IEA.

The comparison between LTES simulation models should be further enhanced, with charging and discharging patterns that are resembling practical applications.

There is a need for numerical modelling tools that are fast and accurate, enabling a faster system simulation and optimisation of LTES integrated into District Heating and Cooling or other large heating and cooling systems.

There is a need for more detailed material and component data that are publicly shared through the materials database.

There is a strong need for practical data on material ageing and deterioration and for theoretical models with which material lifetime can be estimated.