IEA Technology Collaboration Programme

International Energy Agency

Technology Collaboration Programme on Energy Storage

(ES TCP)

Task 39 - Large Thermal Energy Storages for District Heating

Subtask A: Application Scenarios, Assessment of Concepts, Integration aspects

Deliverable A4: Method to carry out an LTES project, important questions & KPIs - Subtask A main report

Task Manager ES TCP Task 39:

Wim van Helden

AEE - Institute for Sustainable Technologies

Austria

AUTHORS

Nathan Fournier, Newheat

Pierre Garcia, Newheat

Pierre Delmas, Newheat

Geoffroy Gauthier, PlanEnergi

Thomas Schmidt, Solites

Abdulrahman Dahash, AIT

Jonas I. Sørensen, Aalborg CSP

Ioannis Sifnaios, DTU

Publication date 05/04/2024

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INTRODUCTION

A directive from the EU requires the implementation of local heating and cooling plans at least in municipalities having a total population higher than 45 000.[1] Large Thermal Energy Storages (LTES) are defined as energy storages able to store 1 GWh over a year, whether they are used as seasonal or daily storages. They represent a great asset for heating planning as they offer various advantages for District Heating Networks (DHN), such as storing very large amounts of thermal energy, providing more flexibility in the network (improved control, expanded energy mix, etc.), increasing the share of renewables and waste heat recovery, peak power shaving, or enhancing power-to-heat (P2H) potential (stabilization of the power grid thanks to P2H).

The four main LTES technologies used in DHN are: Tank (**TTES**), Pit (**PTES**), Borehole (**BTES**), and Aquifer (**ATES**) Thermal Energy Storages, illustrated in Figure 1.

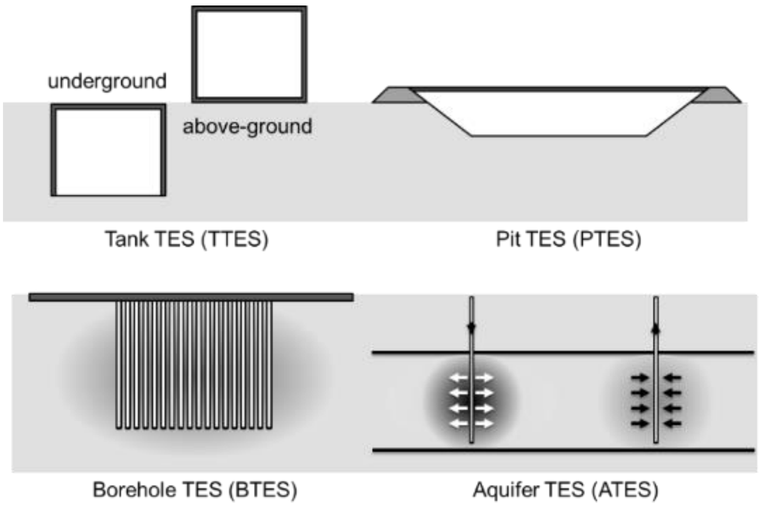

Figure 1 The four LTES technologies considered in IEA-ES Task 39 (source: Solites).

[1] https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32023L1791

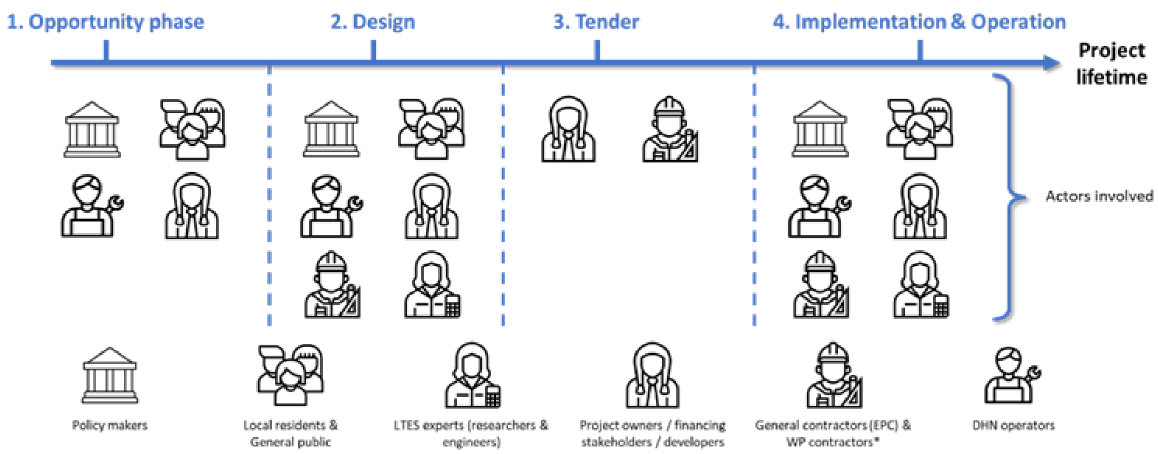

Figure 2: Stages of an LTES for DHN project and actors involved.

An LTES project can be subdivided into four essential stages: Opportunity, Design, Tender, and Implementation & Operation. The main stakeholders involved during each stage are presented in Figure 2.

This report presents LTES project development guidelines and return on experience, presenting first the main stages of LTES project development, followed by case studies. The case studies illustrate key elements of project development for all four main technologies of LTES. The report also introduces typical Key Performance Indicators (KPIs) recommended for pursuing those projects and an example of their use in two case studies, representative of typical LTES applications. The report is aimed at project owners, initiators, or any actor who wishes to enhance LTES development by providing a global vision and a method to master project development.

LTES PROJECT MAIN STAGES AND CASE STUDIES

1. Project main stages, activities, challenges, tools, and indicators associated (see deliverable A1)

1.1 Opportunity

1.1.1 Objective

The main objective of this phase is to identify the technical and economic potential for an LTES application within a given context. Thus, a feasibility study is essential and shall be carried out to cover all necessary background data and investigate the possibilities for different storage applications (e.g., short-term, long-term, and multifunctional storage of heat and/or cold) and the available LTES technologies. In addition, an initial risk assessment, economic estimations, and the identification of potential business cases are part of this study.

1.1.2 Activities

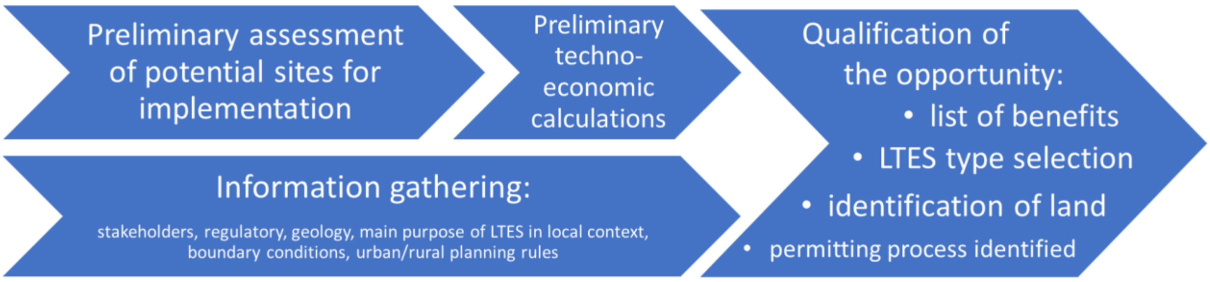

Figure 3. Schematic of the opportunity phase activities

The first step of the opportunity phase is the information gathering about:

- The main goal of the LTES in a given context: store waste heat? store solar thermal heat? store geothermal heat? store heat from Combined Heat and Power (CHP) plants that produce more heat when electricity prices are high? store cold water resulting from a heat pump or a chiller when electricity prices are low (at night for instance)? Or a combination of the above?
- The boundary conditions for the LTES: energy demand profile (daily and seasonal), temperature profile of the supply and return lines (at least seasonal pattern), space availability for construction of the storage or potential sites for implementation, proximity to thermal energy production and consumption entities,
- The different stakeholders involved: local authorities, utilities, companies, and residents,
- Main available constraints for the potential sites (topology, groundwater presence and/or flow, urban planning rules, expansion of living area, soil quality, ownership, etc.).

It is crucial to understand the needs for the DHN to assess if and why LTES is the best solution for them; this consideration is a pre-requisite for justifying the interest of this solution in all future stages. It is usually done by starting a discussion with the main stakeholders. Potential project owners/developers should discuss with the first key stakeholder: municipalities, utilities, DHN operators, main heat producers and end-users as well as local authorities. It is necessary to apprehend the context in which the LTES is to be implemented, in order to list all potential uses for the LTES, since they can be used for various applications, and to gather the first inputs and data from the DHN. In parallel, a discussion should be strategically[2] started with landowners of potential sites and local residents. The list of benefits from the LTES implementation should be presented, as well as the different possible technologies that can be used in order to keep the stakeholders aware of the options available. Potential risks, questions about the technologies and their advantages should be answered during the discussion. To facilitate this discussion, information material about LTES such as the IEA-ES Task 39 brochure can be used as a tool to present the different technologies and some use cases. By having stakeholders involved early on, not only will useful inputs be collected for the opportunity assessment, but local actors will also be more likely to support the project as they will feel included in the project development process[3].

During the discussion with stakeholders, identified sites should be assessed for the implementation of the LTES, together with potential showstoppers: inadequate type of soil for a given type of LTES, lack of space, construction constraints in urban areas, problematic price or ownership of the land. In this stage, preliminary underground investigations can be useful, combined with knowledge of the soil composition based on existing databases. Challenges that could prevent the construction of LTES should be identified early in the process, whether they are due to a technical, economic, legal or environmental aspect. The most suitable sites should be selected, studied and secured (if possible) before moving on to the next stage of the LTES project: the design phase (1.2).

The next step of the opportunity phase is to conduct a techno-economic assessment of the LTES case. For the economic investigation, the calculation of thermal energy generation costs and cost-benefit ratios, as well as a first estimation of investment costs and operational costs have to be performed. These should already include potential subsidies for the investment or for the operations (reduced taxation for instance). Based on these inputs, potential business cases can be derived by making calculations, using for instance early-stage system design tools. Such tools will not determine the design of the LTES but rather highlight and give a first estimate of what kind of technical, environmental and economic benefits the LTES can yield. At this early stage, it is already interesting to consider several business models and start preparing a business plan (see tools of the design phase for more information).

Eventually, the opportunity phase should conclude on whether an LTES would benefit the local energy system or not, and also target the most suitable kind of technologies for the given case. At this point, there can still be several technologies that are relevant to the given context, and only ruled out technologies should be excluded from the next stage.

1.1.3 Common challenges

Some of the most common challenges during the opportunity phase are listed below:

- The availability of land for the installation of an LTES and additional equipment or heat sources (e.g., a solar thermal plant) in close proximity to the heat consumers and existing installations is often difficult to assess. Additionally, in many cases, there can be competing intended utilizations of potential land areas.

[2] It is important at this stage not to say too much too early: if potential sites are communicated too publicly and/or with a too large group of stakeholders, the price of potential sites might increase due to speculation, which could jeopardize the opportunity for the LTES.

[3] Again, strategically sharing information with the public is key to improve the feasibility of the LTES case and can be achieved by making sure stakeholders don't receive too much information too soon, but also by showing the benefits the LTES will bring to the energy system and the society.

- Existing information on hydro-geological ground conditions can be superficial. It can be a blocking point, if it leads to the need for specific drillings requiring the landowners' authorization, which may prove difficult to obtain at such an early project stage. Moreover, the uncertainty regarding prerequisites for approval of an LTES can be high due to a lack of regulations and experiences with comparable projects in the same administrative area.
- Lack of regulatory context specific to LTES in the country of implementation is often a barrier to new LTES projects. The same applies for funding opportunities, which might not include LTES explicitly.
- Information on potential heat sources and heat loads (mass flows and temperatures) that can be charged into or discharged from the LTES are often not available in the necessary level of detail and must be elaborated or estimated.
- In all types of LTES, temperature development inside the storage has a great influence on how much the LTES can be used, and there is a lack of knowledge around the potential and the behaviour of the various LTES at different temperature ranges. For instance, it is often forgotten to count the effect of using a heat exchanger between the DHN and the LTES (temperature drop) during opportunity phase calculations. This issue can be fixed in the design phase, where more detailed modelling tools are used to calculate the real temperatures inside the LTES depending on input and output energy flows, thermal losses, and so on.
- Finding already implemented sites to visit or to use as a reference is not an easy task. Using the dissemination material and references from IEA-ES Task 39, or simply getting in contact with the diverse experts of Task 39 is a good way to overcome this challenge.
- In general, it is complex to make realistic techno-economic calculations in the early stages of an LTES project, due to uncertainties on the boundary conditions, coarse calculation/pre-design tools, lack of knowledge on the specific price of the LTES, on the different costs in the DHN. Therefore, it is advised to get inputs from experts of the field, and make sure to use calculation results not as absolutes, but as indicators of the feasibility of the project.

1.1.4 Means and tools

In many cases, information regarding (hydro-) geological conditions (e.g., geological sequence of layers, presence of groundwater and natural groundwater level, and ground thermophysical properties) can be found in open-source databases, regional geological services, and water authorities. Weather data is available from national meteorological services for various locations, either as measured values or as test reference years generated for designing energy systems.

Information and boundary conditions for the energy system can often be provided by the local energy supply company. Additional information can be collected, e.g., from existing energy production units, heat demand or fuel consumption data, or, in case of new supply areas or consumers, from urban or development plans.

Technical tools used in this phase must be able to consider the collected boundary conditions and produce the required results. Important boundary conditions or interim results are, e.g., the potential heat charged and discharged from the LTES in a time resolution that fits to the application, the intended or considered LTES types and constructions, and the geological conditions at the construction site. Required results are first estimations of the main dimensions of the LTES, energy balance figures as yearly and monthly values, and for many applications as hourly figures. For a proper estimation of the techno-economic potential of an LTES, it is, in most cases, highly recommendable to perform a dynamic simulation of the LTES behaviour and the major parts of the connected energy system already in this phase. This is, because, in contrast to conventional energy systems, the state of charge and the temperature levels in the LTES have to be known in order to be able to estimate the actual potential for charging and discharging the LTES at every moment of the year. However, it is possible in this early stage of the project feasibility to use simplified tools, that do not model precisely the LTES thermal behaviour, as long as they take into account a realistic behaviour of the LTES. Simplified tools should include, as much as possible, thermal losses (adapted to the type of technology and use considered), limited heat capacity depending on operating temperatures of the energy system, realistic thermal capacity input and output of the LTES (depending on the type of LTES considered), etc.

Due to the uncertainties in techno-economic boundary conditions as well as in calculation methods available for the early stages of an LTES project, a crucial tool is the use of sensitivity analysis. Parameters used as an input to techno-economic calculations should be varied to validate the potential of LTES also when using different boundary conditions (investment costs for the LTES, temperatures on the network, amount of available waste heat, yearly heat demand, etc.).

1.1.5 Indicators

The following table introduces the main KPIs of interest for the different actors in this stage. It is presented in each project stage to summarize the interests of each party. This table is not exhaustive, and the list of indicators available in Appendix 1: KPIs list, provides a more insightful view on the topic.

<table>
<tr><th>Actor</th><th>Technical indicator</th><th>Economic indicator</th><th>Environmental indicator</th></tr>
<tr><td>
Policy makers</td><td>- Technology
- Location / land area required
- Heat transfer fluid and storage medium
- Size of the DHN / heat demand / number of households impacted
- Storage lifetime / project start date
- Heat source energy fractions with or without LTES & percentage of renewables</td><td>- DHN weighted marginal heat price with or without LTES</td><td rowspan="4">- Type of impacts to foresee (environment / local residents)
- Energy specific CO_2 emissions with or without LTES</td></tr>
<tr><td>
Local residents & General public</td><td>- Technology
- Location / land area required
- LTES volume (compared to concrete values)
- Size of the DHN / heat demand / number of households impacted
- Storage lifetime / project start date
- Heat source energy fractions with or without LTES & percentage of renewables</td><td>- DHN weighted marginal heat price with or without LTES</td></tr>
<tr><td>
DHN operators</td><td>- Technology
- Location / land area required / distance to integration point
- LTES volume
- Operation temperature range (Heat transfer fluid AND storage medium)
- Heat source energy fractions with or without LTES & percentage of renewables
- Identification of post-heating technologies for boosting the discharged temperature</td><td>- DHN weighted marginal heat price with or without LTES
- Heat generation cost</td></tr>
<tr><td>
Project owners / financing stakeholders / developers</td><td>- Technology
- Location / land area required / distance to integration point
- LTES volume
- Heat source energy fractions with or without LTES & percentage of renewables
- Modelled charged and discharged heat
- Surplus energy available and targeted heat from the DHN to be addressed
- Design storage capacity
- Storage lifetime / project start date
- Heat source energy fractions with or without LTES & percentage of renewables</td><td>- DHN weighted marginal heat price with or without LTES
- Heat generation cost</td></tr>
</table>

1.2 Design

1.2.1 Objective

In LTES projects, the design and planning phase plays a critical role as it emerges 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. The design phase involves comprehensive studies encompassing technical, economic, regulatory, and environmental aspects essential for successful project implementation. Herein, a wide list of variables (e.g., LTES type, construction method, size, geometry, envelope, soil conditions and interaction with groundwater) is iteratively evaluated in order to achieve the optimal LTES. This phase benefits from the preliminary investigations made in the opportunity phase, whereby potential feasibility of certain types of LTES might already have been excluded. Moreover, the detailed clarification of constraints during this phase leads to validated technical viability, economic feasibility, and reduced environmental impact of the LTES design. Furthermore, this phase plays a crucial role in the determination of the optimal type, size, and geometry of the LTES system. In this context, Figure 4 illustrates a list of variables which can be used to define the design and prepare the planning phase of LTES, classified into 4 categories. The complexity observed in this phase for LTES technologies is noticeable.

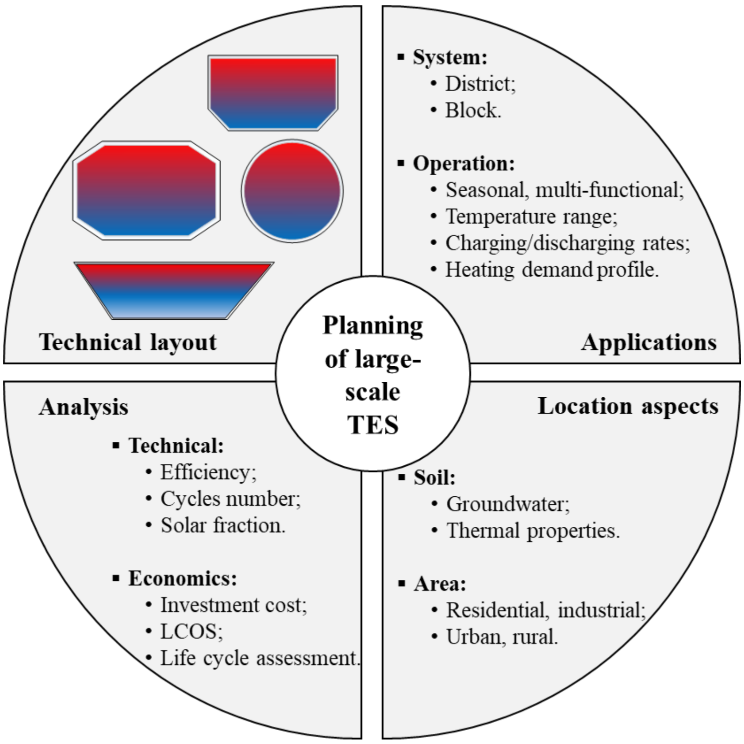

Figure 4: An exemplary representation of some influencing parameters on the planning of large-scale underground TES and its economic feasibility (reproduced from (Dahash, A., Ochs, F., and Tosatto, A., 2021)).

1.2.2 Activities

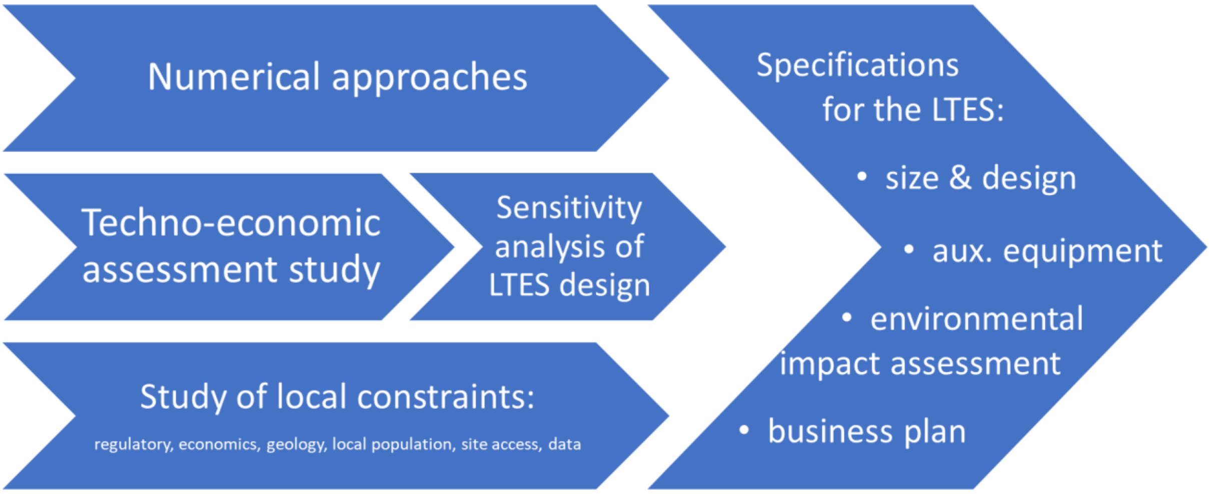

Figure 5. Schematic of the design phase activities

The design phase launches its activities with numerical approaches to simulate the dynamic thermo-hydraulic behavior and estimate the performance of the considered LTES. This step is frequently seen as a crucial one. Typically, it involves exploiting sophisticated tools and modelling techniques to carry out detailed simulations to comprehensively assess the LTES system performance under diverse conditions (see Figure 4). The utilization of these tools enables engineers and designers to gain further insights into LTES, properly adjust LTES parameters, optimize heat transfer methods (e.g., charging/discharging), and ensure reliable LTES efficiency.

Additionally, conducting a comprehensive economic feasibility assessment study is also crucial. Such a step involves specific cost estimation, evaluation of potential returns and payback periods, and exploration of diverse funding opportunities. This stage also encompasses the critical task of securing the necessary land needed for the chosen LTES. Accordingly, the exploration of potential public financing support becomes relevant. The proposed LTES should eventually be capable of showing a sustainable economic outlook for the project.

On the other hand, a comprehensive site analysis plays a significant role. This involves identifying and inspecting specific local constraints and regulatory frameworks, such as existing buried networks and geological context. Understanding such site-specific factors (e.g., soil conditions, potential groundwater presence, or other subsurface conditions) proves to be critical in avoiding complications throughout the course of construction. It further ensures the long-term stability and efficiency of the LTES system. Therefore, it is necessary to carry out environmental impact assessments and address the necessary permits as they are pivotal steps in this phase. These assessments ensure compliance with regulations and thoroughly evaluate potential ecological impacts.

Then, the establishment of technical specifications and constraints is an integral part of this phase. This includes the investigation of possible LTES geometry, construction materials, and sizing parameters. Those specification and constraints can result from the site analysis mentioned above. Besides, the selection of an appropriate construction approach is equally critical. Thus, many choices and decisions are often met during this phase, and they might significantly affect LTES durability, efficiency, and overall functionality. Moreover, the project technoeconomic feasibility can be directly affected by those geotechnical and hydrogeological constraints for all LTES types and at different degrees. Consequently, the involved engineers focus on aligning specifications with project goals while ensuring continuous compatibility with the chosen construction method. In a later step, sensitivity analysis of the LTES design stands as a crucial aspect of the design phase. Herein, engineers evaluate how variations in key parameters impact system performance (e.g., technical, economic, and environmental).

At the end of this phase, technical specifications to anticipate for the implementation phase should also be done such as the preparation of an instrumentation plan. This plan should anticipate all the data that will be required during the operation period, for monitoring, fault detection, performance analysis…

1.2.3 Common challenges

In the design phase, several challenges may arise due to the absence of specific regulatory frameworks in certain regions or administrative delays emerging from the limited experience in the authority approval process. In order to overcome such delays, it is crucial to continue proactive engagement with regulatory bodies started in the opportunity phase, advocating for processes and ensuring early compliance with predefined regulations. Other delays can take place in the subsidy instructions disrupting project timelines. To mitigate this challenge, it is crucial to ensure open communication channels with relevant authorities. Besides, timely and clear documentation should be continuously carried out together with contingency plans to manage potential delays.

Other challenges can be observed in modifying input data and boundary conditions throughout the design process. This necessitates running new simulations that might affect project planning and design. Therefore, the implementation of a robust iterative simulation process and maintaining flexibility in LTES design can help in accommodating dynamic changes effectively. Another challenge can be the definition and exploration of new control strategies in order to address further flexibility offered by LTES. Additional challenges can be highlighted by the difficulty of ensuring suitable discharging methods for high supply temperatures in District Heatin (DH) systems – especially in extreme weather conditions, it is crucial to maintain the LTES at a secured capacity. Therefore, it is important to integrate and collaborate with experts to initiate innovative control mechanisms and explore further solutions for varying conditions.

Other technical challenges emerging from soil quality, groundwater presence, or flow can result in significant obstacles during the construction and operation phases of LTES. To effectively address these challenges, the thorough site analysis mentioned previously will help making a list of protective measures that are tailored to overcome site-specific constraints.

Other challenges on the social level can be the local/regional unacceptance due to insufficient understanding of the LTES benefits or lack of community involvement, which can hinder progress. To overcome this type of challenge, it is necessary to proactively engage with stakeholders, support programs to raise awareness, and conduct a transparent dialogue to address concerns and showcase the LTES advantages within future energy systems, during this phase, but also at the earlier stage of the project (opportunity phase).

1.2.4 Means and tools

The utilization of several means and tools in the design phase ensures a multidimensional approach that covers technical, economic, and environmental aspects. The integration of such tools systematically assesses an informed decision-making process, enabling project stakeholders to design and plan LTES projects that are technically optimal, financially feasible, and environmentally sustainable.

Therefore, several simulation tools equipped with sophisticated modelling techniques including energetic and thermo-hydraulic approaches are utilized. Engineers and planners rely on these tools to carry out detailed simulations that not only lead to specific technical specifications but also optimize system designs for efficiency and performance. Such tools are usually calibrated and validated against measurement data from existing LTES (Dahash, A., Ochs, F., Tosatto, A. and Streicher, W., 2020), or tested against each other on theoretical cases (Ochs, F., Dahash, A., Tosatto, A., Reisenbichler, M., O'Donovan, K., Gauthier, G., Kok Skov, C. and Schmidt, T., 2022) (Dahash, A., Ochs, F., and Tosatto, A., 2021). To ensure the economic feasibility of the LTES, it is also crucial to properly estimate the costs associated with the LTES project for an effective decision-making process.

The environmental impact assessment studies serve as a cornerstone in LTES design that evaluate the potential environmental implications of the LTES project. It can include studies regarding fauna, flora, surrounding housing, underground life, and geotechnical and hydrogeological studies. Such assessments help ensure compliance with regulations and provide crucial insights into ecological effects to lead the decision-making towards sustainable practices. Therefore, it is important to understand the geological and soil conditions at the project site. Geotechnical specifications aid in realizing subsurface conditions, which enables engineers to anticipate and mitigate potential challenges that may arise during LTES construction.

Moreover, following the first economic investigations from the opportunity phase, developing a robust business plan can help map out the technical viability and economic feasibility of the LTES project. This comprehensive plan encompasses financial projections, risk assessments and strategies for funding, highlighting the LTES sustainability and potential returns on investment. It finalizes the preliminary techno-economic calculations made during the opportunity phase, which were indicating the potential of LTES in the given context.

During the preparation for the tender phase, it is important to have reached a clear and detailed business plan: who makes the investment, what benefits do the different stakeholders get in return, what sources of revenue are there, what are the expenses (legal, operational, maintenance), how long does it take for the investor to make a return on investment, who pays who and when. The business model (how the value is created in the project), which is described in the business plan, can vary significantly for a given type of LTES. For instance in Denmark, a Pit Thermal energy Storage (PTES) can be an investment for a DHN operator, which can own the PTES, and use it to deliver renewable heat to its customers (see for instance the use case of Dronninglund introduced in deliverable A2 "LTES project development case studies"), but it can also be owned by several DHN operators (see for instance the use case of Høje Taastrup), and benefit the entire energy system of a city (in that example Copenhagen). In the second case, all the actors that benefit from the balancing offered by having the PTES in the energy system, pay back the loan of the PTES, proportionally to the benefit they get. The first discussions regarding the business plan should start as early as the Opportunity phase and should be concluded when closing the design phase.

1.2.5 Indicators

The design phase is a follow up of the opportunity phase, thus the indicators introduced in the previous part are still relevant in this part and only additional indicators are introduced in the following table.

Actor	Technical indicator	Economic indicator	Environmental indicator
 Policy makers		- CAPEX & OPEX	- Hydrogeological effects - Thermal effects and extent of the heating zone - Changes in groundwater chemistry - Changes in microbial population - Reduction in CO2-emissions
 Local residents & General public	- Share of renewables in heat generation portfolio - Share of stored heat in annual heat supply	- Increase/reduction in heat supply tariff	- Hydrogeological effects - Changes in groundwater chemistry - Reduction in CO2-emissions
 DHN operators	- Modelled charged and discharged heat - Number of heat storage cycles per year	- Expected cost of backup heating unit to lift the temperature to the one of DHN	- Hydrogeological effects (i.e. groundwater/ground temperature)
 Project owners / financing stakeholders / developers	- Storage losses - Energy efficiency - Number of heat storage cycles per year - Annual refill volume - Soil characteristics - Slope & depth	- Cost of the energy used to charge the LTES - CAPEX & OPEX	- Hydrogeological effects - Thermal effects and extent of the heating zone - Changes in groundwater chemistry - Changes in microbial population
 General contractors (EPC) & WP contractors	- Design parameters of the corresponding work package LTES components - Performance indicators of the corresponding work package LTES components	- CAPEX & OPEX	
 LTES experts (researchers & engineers)	- All design parameters - Modelled charged and discharged heat - Storage losses - Energy efficiency - Number of heat storage cycles per year	- DHN weighted marginal heat price with or without LTES	

1.3 Tender

1.3.1 Objective

During this phase, the general contractor, or the different subcontractors are chosen based on a defined scope of work. The different offers can be compared using the KPIs listed below. Contracts need to correctly balance the role and responsibilities of each party based on their knowhow, experience and size compared to the work to be done to make the project ready to be financed. The tender process usually starts during the design phase to test the market and gets updated prices during early development phases.

1.3.2 Activities

Figure 6. Schematic of the tender phase activities

- Work Package (WP) distribution established, interfaces clarified and listing of requirements for each WP,
- Tender documents preparation,
- Evaluation, negotiation, and technical adjustment phase,
- Selection of the best offer considering specific criteria defined by the project owner,
- Contractualization based on a clear and balanced distribution of responsibilities.

The tender phase is prepared during the design phase, as explained at the end of the previous chapter: all constraints for implementation have been gathered and used to establish the appropriate design of the LTES, as well as the auxiliary equipment and constructions (district heating pipes, technical building, water treatment plant, buffer water reservoirs if needed, pumps and heat exchangers, etc.).

Based on the specifications established in the design phase, the upcoming work required for implementation of the LTES is divided into work packages. This first step is key to ensure the success of the project.

In general, two different approaches can be followed:

1/ Separate the work in different WP:

Increasing the number of work packages allow to make sure the right company is selected for every work to be performed, based on its specific competency and its references. This approach allows to facilitate the selection of local companies to perform “simple” tasks at a more competitive price.

This way to proceed generally leads to a lower global price as it prevents the addition of mark-up when different subcontracting layers overlap.

On the other hand, it requires much more specification effort as all contractual conditions (mainly **price, schedule, and performance**) needs to be expressed for each work package. Moreover, the work needed to clarify and check interfaces between work package is significant and a possible source of mistakes.

During the construction phase, more work will be assumed by the project owners or any support he will hire to coordinate the different companies and assume the security on site. For the takeover phase, all interfaces can become a source of complexity and a possible additional cost for the project owners.

2/ Select a unique turnkey supplier:

The main benefit of this option is the clarity it brings in the responsibility of each party as it allows to limit the interfaces to the very minimum. The contractual conditions (mainly **price, schedule, and performance**) are expressed for the whole project, making it more accessible to the project owner and financing parties. The efforts are reduced to the minimum for the project owner, for the following stages of the project.

This way to proceed generally leads to a higher global price as it adds mark-ups at each subcontracting layer of the project structure. As the turnkey provider assumes alone all commitments for the whole construction, it needs to get paid in consequence.

On the other hand, this organization implies that all the success of the project relies on one player. This highlights the need for the selected company to be competent in all works and techniques it will drive for the realization of the project to correctly manage the interfaces and the overall price, schedule, and performance of the system supplied.

This option often limits a lot the number of relevant candidates as LTES are still new and innovative with limited number of references, especially if you consider turnkey project references.

Obviously, there are several intermediate work distribution strategies to be considered depending on each project specificities. The following list presents some typical WP distributions encountered for the different LTES technologies:

Typical WP distribution encountered for the different LTES technologies:

- TTES: 2 to 4 work packages
    - Foundation and other civil works,
    - Tank parts supply and tank construction + insulation and facing,
    - Process building, pumps, valves, pipes, instrumentation,
    - Water filling & water treatment.
- PTES: 4 to 10 work packages
    - Excavation/soil works,
    - Piping, diffusers, process building, pumps, valves, instrumentation,
    - Liner installation,
    - Water filling & water treatment,
    - Cover supply and installation.
- BTES: 2 to 3 work packages
    - Boreholes drilling and casing, other soil works,
    - Process building, pumps, valves, pipes, instrumentation.
- ATES: 1 to 3 work packages
    - Boreholes drilling and casing, pumps and injection valves,
    - Piping between wells and process building,
    - Valves, pipes, instrumentation and process building.

In the LTES sector, still under development, project owners should give a significant value to **previous references**, making sure construction companies made the effort to integrate, in one way or another, some return on experience from first demonstration projects.

On the other hand, the sector still needs for innovations to improve its competitivity, and any new solution needs to be assessed properly before being deployed at large scale.

Each work package should include a given number of criteria to be met by the proposals:

- **Price:** It can be difficult to make sure the scope of work is comparable to enable a fair price comparison.
- **Construction schedule:** Schedules need to be analysed and compared, taking the limitation of liability in consideration (depending on weather conditions or other external factors). LTES construction schedule can be impacted by different sources of delays, sometimes difficult to foresee.
- **Durability warranty:** LTES are long term infrastructures. Any commitment from the supplier on the durability of the supplied system needs to be carefully analysed, including detailed warrantee conditions. These warranties can bring a significative value to the project.
- **Performance warranties:** Performance warranties can be adapted to correspond to real operation conditions envisioned in the project. Any KPI used during the Design phase can become an indicator used as a reference for warranted performance checks as long as:
    - a **verification method** (including its uncertainty and a metrological process associated),
    - a **threshold value**,
    - and a **compensation penalty** can be accepted by all parties.
- **Use of standardised methods and quality checks:** To avoid complex contract management, the description of quality checks and any standard (ISO, EN or national standards) related to the work to perform must be favoured.

The construction contract(s) need to mention the main conditions described in the proposals. Clearly defining the role and responsibilities of each party will help the project implementation.

For LTES infrastructure innovative project, the writing of the contracts in a descriptive and didactic way will help the parties during the contract implementation phase.

Main paragraphs of the contract are commented below, taking as a basis the same structure as the proposals:

- **Price**:

As LTES projects can take time, the price indexation described in the contract should be closely analyzed to understand the main parameters driving the price during the time between the signature of the contract and the different payment steps to be agreed upon.

- **Construction schedule:**

Penalties in case of delays needs to be described. The amount of the penalty is calculated according to the damage caused by the delay.

- **Durability and performance warranty terms and conditions:**

Warranties terms and conditions should be attached to the contract, as part of it. Depending on the KPIs used for performance check, the detailed description of a verification method can be useful to avoid misunderstanding and interpretations.

- **Standardised methods and quality checks:**

Should be mentioned, described and/or attached to the contract, as part of it.

- **Context and boundary conditions:**

To make sure all parties are aware of the applicable constraints, they should be attached to the contract, as part of it. This will avoid future negotiation on price, delay, or responsibility in case of breach. As an example, all drawings, layouts, or documentation related to the building permit should be attached to make sure the construction company is aware of them and to ensure the project is compliant to it.

Typical articles considering people security, confidentiality, commitments from each party, expected insurances, payment conditions (possibility to use bank guarantee to secure first payments), applicable law and dispute resolution, etc. should also be included in the contracts.

1.3.3 Common challenges

- Projects owners have the responsibility to express the structure of the tender, each WP scope of work, as well as the technical and non-technical specifications. If a new event occurs during project construction, constructions companies will be legitimate to ask for adjustments (in terms of price and/or delay and/or performances commitments). LTES all have an important interface with the ground and underground. It is therefore crucial to make sure the ground and underground investigations are clear and complete, to express it in the Specifications and avoid future changes in the contract execution. It is often difficult to make the different suppliers' offer comparable in terms of scope of work and level of quality. The best practice consists in comparing strong commitments from suppliers, whether assumed through product and performance warrantees of at least measurable standardised KPIs, being comparable between different offers.
- The project contractual setup (Structuring in WP or realized as a turnkey contract) can lead to numerous and complex interfaces description leading to some risks for the project owner if some work needs to be performed in addition to the main contracts signed at the end of the tender phase.
- It can be difficult to estimate the capability for one candidate to realize the work in a proper way. This can be solved by asking for the support of experienced advisors having participated to previous references of the chosen LTES technology, or by selecting a contractor company able to present relevant references with the chosen LTES technology.
- The only LTES construction standard known as of now, is for TTES (BS EN 14015:2004). This Standard can be used by the project owner as a reference for the design and/or construction phase. As of today, there is no Standard (National, Continental or ISO), to describe the other LTES onsite performance check, to be realized when the Client takeover the system to start the operation phase. This situation makes it a challenge, for both parties (client and supplier) to agree on:
    - an **indicator**
    - a **performance check method** and
    - a **level of performance**

  driving the performance check to be realized to ensure the performance warranty offered by the supplier.
- Updated price and financing conditions sometimes differ from the hypothesis used in earlier stages of the LTES project development. This can lead to a price increase, confirmed just before

construction, after years of project development. This would result in some delays in case this situation has not been discussed and shared between all parties of the project.

- As LTES are still innovative solutions, the time needed to evaluate the different offers received should not be underestimated, as they will probably require time for technical adjustment.

  Offering some flexibility to the construction companies in this adjustment phase will help the project to move forward on a good basis for the contractualization phase. Construction companies can offer alternative schedule, alternative materials, construction method and planification, an alternative KPI used as performance warranty check which would make them more comfortable while entirely or partly fulfilling the project owners' expectations.

  This flexibility could lead to a more robust and mastered offer and eventually lead to a lower price or better warranty conditions.

1.3.4 Means and tools

The tender documentation is key to ensure that the project owner selects the right partners for the LTES realization.

It gathers all the technical, legal and environmental specifications for each work package, and includes some criteria to define what requirements need to be fulfilled by the offers.

It can also provide auxiliary criteria which can favor an offer compared to another, such as the possibility for one candidate to bid on different WP, thus limiting the number of interfaces, or the option to propose a different design for a given part of the LTES.

Simple comparative table of offers can be used to ensure all decision criteria are taken into consideration and facilitate the comparison of different offers.

In case of proposals significantly deviating from the specifications, with for instance price, performance or durability, updates of the project Business Plan can be realized if the proposed solution remains eligible.

EPC contract(s) need to be signed to secure the terms and conditions of the WP scope design, procurement, and construction phases. Take-over phase and performance checks methodologies description needs to be included in the contract.

1.3.5 Indicators

The following table introduces the more relevant indicators for each participant in the tender phase.

Actor	Technical indicator	Economic indicator	Environmental indicator
 Project owners / financing stakeholders / developers	- Key performance indicators of the corresponding work package LTES components	- Updated DHN weighted marginal heat price with or without LTES - CAPEX of the project - OPEX estimations Typically, you can express each Work Package in €/m³ or €/m² to easier compare different offers.	Any environmental restriction (and its related KPI) imposed by the administration in the permits obtained needs to be requested
 General contractors (EPC) & WP contractors	- Key performance indicators of the corresponding work package LTES components	- CAPEX of the package	Any environmental restriction (and its related KPI) imposed by the administration in the permits obtained needs to be ensured

1.4 Implementation/Operation

1.4.1 Objective

During the construction phase, the LTES is built and connected to the district heating network. Subsequently, it is commissioned and operated for the duration of its planned lifetime. All the stages are highly dependent on the LTES technology, and experienced consultants and contractors should be included in the process to avoid unnecessary delays and risks. In the following, an example of the implementation of a PTES is given, along with known challenges.

1.4.2 Activities

Figure 7. Schematic of the implementation & operation phases activities

First, the LTES is constructed and commissioned and subsequently moved to the operation phase, including service and maintenance. The construction process is specific for the type of LTES, e.g., the process of constructing a PTES is summarized below:

1) Excavation of soil to create the desired pit geometry (if it is needed, the processing and evacuation of the excavated material can be a stage in itself for other LTES)
2) Repurpose the excavated soil for use as embankments.
3) Installation of diffusers and pipes, including foundation work.
4) Sealing of the pit with polymer liners and cover the pit with a temporary/sacrificial liner.
5) Water filling below the temporary liner until the pit is full.
6) Removal of the temporary liner and installation of the permanent liner together with manholes and ventilation channels.
7) Construction of the insulated lid.

A similar step-by-step procedure can be made for the other LTES technologies, which includes drilling the boreholes or erecting the tank and other specific tasks for the BTES or the TTES respectively. The common denominator in the construction process for all the technologies is that it is a large project which involves time-consuming steps.

For the PTES, all the components are built on-site from materials that are shipped to the location. The liner is installed on-site by welding together strips of it, and the insulated lid is installed by layering specific insulation materials and sealing them. The quality of the components is ensured during the installation by pressure testing the liner welding seams, measuring the gaps between insulation boards and examining the interlocking pattern between layers of insulation. It is common for an inspection and test plan to be used to assure the quality of the installed components.

The commissioning of the PTES begins when the insulated lid is installed, and the diffuser pipes are connected to the charge and discharge pumps. The commissioning phase involves testing the charge and discharge rate and monitoring the stratification inside the storage. A part of the commissioning phase is to review the performance tests of the system. Currently, no formal performance tests of the PTES exist; however, a framework is being developed by Aalborg CSP for the insulated lid. The performance tests should include the following in summary:

- Test the rainwater drainage system's pumping capacity and the mechanical and electric connections,
- Test the insulation materials of the lid by monitoring the temperature distribution inside the lid and comparing it to the expected distribution,
- Test the durability of the insulation materials by monitoring the temperature and humidity inside the lid and confirming that it is within their permissible operating conditions.

After the commissioning phase, the operation phase starts, where maintenance is required. The maintenance of a PTES involves inspecting the lid weekly and monthly to check on the rainwater pumps. It also includes monitoring the data from the sensors inside the lid and those associated with the rainwater pumps. This is often made as an automatic system that sends a message or warning to the operator if any value is outside the permittable range. Adjustments to the water level and the pH value of the storage water is also required since water expands as it is heated and due to water loss as water vapor diffuses through the lid structure. In addition to the PTES, the associated pumps and heat exchangers also require service. External actors, such as notified body or testing organism, can be involved for checking regulatory and implementation compliance.

All the components of the PTES are designed to have a service lifetime of a minimum of 25 years.

1.4.3 Common challenges

The construction phase of the PTES involves multiple steps, each with its own requirements, and some of them are performed by different contractors, thus creating interfaces that need to be managed. Normally, challenges arise, and the most common challenges are outlined below.

The construction of the PTES involves steps that are weather-sensitive. The liner welding requires an ambient temperature above 5°C and no rain, and excavation is preferred when the soil is not frozen. Thus, the construction process is planned to avoid these difficulties.

One of the major time-consuming parts of the construction process is the water filling. This process involves supplying the water and treating it by reverse osmosis technique. It is highly recommended that the water supply is confirmed prior to the construction phase, as this minimizes the risk of delays.

It is possible to get delayed during excavation due to some unexpected archaeological findings; however, the severity and probability of this are related to the country. Additionally, the soil composition and the groundwater conditions should be as expected from the geotechnical survey conducted during the design phase.

The operation phase involves testing the entire system, PTES, pumps, valves, heat exchangers, etc. and typically exposes any bottlenecks. Experience shows that improper choice of valves, pumps or heat exchangers can lead to a lower charge and discharge rate than expected.

1.4.4 Means and tools

The engineering team design and modelling tools are used for providing specifications for the construction, they are usually used in the design stage and their results give guidelines to the construction team.

The instrumentation plan designed before starting the storage construction is used for specifying all the sensors which should be implemented. For PTES the most important ones are temperature sensors distributed vertically in the water, and flowmeters and temperature sensors at the different inlets/outlets to monitor the flows going in and out of the storage. Moreover, it is common practice to install temperature sensors around the PTES in the soil, especially in funded projects or if it is required by the authorities to monitor the soil temperature. It is also common to install temperature, humidity, and heat flux sensors inside the lid. This enables the operator to monitor the system in more details and provide extra data for a digital twin or for research purposes, e.g., material science.

A supervision system is also necessary to monitor the behaviour of the storage continuously. It provides live measurements from the instrumentation and is used for various purposes, performance measurement, fault detection… To do so, periodical data extraction and analysis is conducted. This data is crucial for quality insurance, hence the importance of well-designed instrumentation specifications.

Finally, operation & maintenance planning and work is necessary. A planning of the periodical maintenance tasks is realized, and more specific maintenance can also be conducted depending especially on fault detection.

1.4.5 Indicators

The main indicators monitored by the actors of the project during the construction and the operation phases are listed in the following table:

Actor	Technical indicator	Economic indicator	Environmental indicator
Policy makers			- Environmental indicators from the KPI list to control according to regulation
Local residents & General public		- DHN weighted marginal heat price with or without LTES	- Local area impact during and after implementation (visual, acoustic, traffic disturbance…) - Changes in groundwater chemistry - Ground temperature increase
DHN operators	- Annual charged and discharge heat - Heat losses - Efficiency - Number of heat storage cycles per year - Auxiliary power consumption	- DHN weighted marginal heat price with or without LTES	- Environmental indicators from the KPI list to control according to regulation
Project owners / financing stakeholders / developers	- Annual charged and discharge heat - Heat losses - Efficiency - Number of heat storage cycles per year - Auxiliary power consumption - Stratification indicators	- DHN weighted marginal heat price with or without LTES - Evolution of CAPEX & OPEX	- Environmental indicators from the KPI list to control according to regulation - Changes in groundwater chemistry - Ground temperature increase
General contractors (EPC) & WP contractors	- Performance indicators of the corresponding work package LTES components - Auxiliary power consumption of the corresponding work package LTES components	- Evolution of CAPEX & OPEX	
LTES experts (researchers & engineers)	- Measurements from the various sensors of the project - Stratification indicators - Efficiency		- Environmental indicators from the KPI list to control according to regulation - Changes in groundwater chemistry - Changes in microbial population

2. Project development case studies (see deliverable A2)

2.1 TTES case study

1. PROJECT ID: BERLIN (GERMANY)

Type of usage: daily storage of heat
Year commissioned: 2023
Owner: Vattenfall
Technical details — Water volume: 56'000 m³ — Dimensions: Ø 43 m x h 45 m
Storage capacity: 2'750 MWh
Charge-discharge capacity: up to 200 MW_{th}
~70-120 cycles of charge/discharge per year
Max operational temperature: 98°C (atmospheric)

2. MODELLING AND SIZING

The demand for storage was assessed in a study assessing different sites, LTES technologies and possibilities based on the DH-demand and plant/network boundary conditions (http://dx.doi.org/10.5445/KSP/1000023676). During this project stage, techno-economic simulation and optimization was conducted on a system level using an internal MILP tool for energy system optimization as well as the software Bofit. Data for boundary conditions (heat load curves, weather, DHN integration points, etc.) was already available internally for other purposes. For the design of the storage a feasibility study was concluded to specify used technologies and design parameters. During this stage Excel and Ebsilon were used to analyse the storage and the site integration.

3. STORAGE MATERIALS

Conventional materials were selected based on operation and environmental boundary conditions (temperature, mechanical resistance, insulation properties, etc.) and under consideration of the tank dimensions.

4. LAND

Different power plant locations (operator owned) were compared before selecting the final location. The location was selected primarily based on its proximity to the generation units and availability of space. The chosen plant site is located at a river and therefore groundwater is found relatively shallow. A soil survey was carried out to determine the requirements of the foundation.

5. PERMITTING PROCESS[4]

Local urban plan can restrict the maximum height of a construction, which was not the case for this project; however, the city hall requested that the TTES be moved due to its visual impact for the neighbourhood, which creates little shadowing on the solar field sometimes of the year.

The storage has been built above drinking water collection areas, thus a hydrogeologist had to control that the foundations construction would not impact the aquifers.

[4] Those parts are written based on Newheat's projects in Narbonne to complete data gathered from Berlin project.

6. CONTRACTUAL SCHEME

Vattenfall owns and operates the plant, the contractors build it. The contractors provided both performance and mechanical warranties.

7. TENDERING PROCESS

The tendering process was divided into 3 main work packages/lots:

- Civil works including the heat storage plant, pipe bridge and pump station building,
- Design, construction, and erection of the heat storage tank,
- A general contractor for basic and detail Engineering of the pumping station plant, auxiliary systems, procurement, erection, and commissioning.

8. CONSTRUCTION[4]

During the construction, some neighbours showed concerns regarding the visual impact of the project, as no other significant construction are visible in this area.

A truck crane and baskets are used to erect the storage, thus if the wind exceeds a certain limit, the operation must be paused.

No performance test measurements have been realized but CFD studies have been conducted on similar project to verify that the storage would respect the contract requirements.

9. OPERATION & MAINTENANCE

The TTES, which is currently still in commissioning phase, is thoroughly instrumented. The measurements generally work as expected so far and will provide insightful and useful information about its operation. Additionally, a special optical temperature measurement is installed in the storage tank so that together with TU Dresden, real temperature profiles and operation models can be read and studied as soon the storage goes into operation (Project TWINopt). Currently there are no maintenance activities planned in the short-term since the TTES is not yet in operation.

2.2 PTES case study

1. PROJECT ID: DRONNINGLUND (DENMARK)

Type of usage: seasonal storage of heat
Year commissioned: 2014
Main heat source: Solar thermal
Owner: Dronninglund district heating (Denmark)

Technical details:
- Water volume: 60’000 m³
- 16 m deep
- Storage capacity: 5’000-5’500 MWh
- 2-2.5 cycles of charge/discharge per year
- Max operational temperature: 85-90°C (in summer)
- Lid dimension: 91 m x 91 m
- Slope 1:2
- Charge-discharge capacity: 27 MW_{th}

2. MODELLING AND SIZING

It was relatively easy to access data regarding existing DHN as well as load curves and temperature requirements from the control system at the plant. Weather data is also easily accessible through meteorological services. The difficult part was the boundary conditions on geotechnical parameters as soil parameters, and ground water flow. Geotechnical conditions were estimated from knowledge on the soil type as well as geotechnical drillings/investigations.

PTES technology was selected for this project because of the following reasons:

- ATES was not considered due to limitations of temperature and the fact that there is no cooling demand,
- TTES was not relevant due to size and cost considerations and due to the high solar fraction target for the project (close to 50% coverage from the system solar + storage + heat pump),
- BTES was considered but PTES was chosen due to higher flexibility (fast charge/discharge) and higher temperatures giving more direct utilization of the storage without permanent heat pump operation.

TRNSYS modelling was used for sizing the PTES and assessing its performance. The models used evolved through opportunity and design phases: system was changed and (re)optimized a few times due to change in expectations to legal framework (electricity taxes, taxes on fuel – bio-oil, natural gas etc.). Consequently, an electric heat pump was replaced by a heat-driven heat pump in the design phase.

3. STORAGE MATERIALS

The liner material was chosen based on high expectations and guarantees from the supplier regarding service life at 90°C. Insulation material and properties were chosen based on experience from earlier pilot storages (Marstal 10'000 m³ storage, Ottrupgaard 1'500 m³ storage). The lid was replaced in 2021, with a new design of the cover based on experience from original design in Dronninglund as well as experience from other PTES in Denmark. Material was selected based on moisture simulation and diffusion principles.

4. PERMITTING

A local plan has been elaborated, which introduces the new energy plant and describes all consequences for landscape and environment. It includes permissions regarding the Law of Heat Planning, the Law of Nature Protection, the Law of Environmental Protection, and the Municipal Plan. On top of that, a screening of environmental consequences was elaborated to assess the need for an Environmental Impact Assessment report.

The first decision stated that there was no need for such a report, but following a complaint the report was requested, as the consequences of using groundwater for filling the storage was not described.

5. TENDERING PROCESS

The tendering process was divided into 5 main work packages (lots):

- Excavation/soil works,
- Piping, diffusers, technical installation,
- Liner installation,
- Water filling,
- Cover installation.

The contractualization with contractors was based on standard Danish building contracts (ABT 93/ABT18).

6. CONSTRUCTION

The weather conditions had a minimal impact on the construction works. Mainly functional tests were done for commissioning.

7. OPERATION & MAINTENANCE

There has been issues with different sensors:

- Level sensors and moisture sensors showed short service life,
- Temperature sensors work properly, but some of them inside storage have been changed due to lightning damage.

Relatively strong focus was given on instrumentation and data analysis as it was a public funded project. It has also been part of other funded projects with continuously monitoring of performance between 2014 and 2021, and live data has been uploaded on https://varmelagerdata.dk/.

The main maintenance activities planned were monitoring and inspection of water level and rainwater pumps. Unexpected maintenance activities had to be conducted on the original cover to remove rainwater and replace insulation due to combination of heavy loads from rainwater puddles and high temperature/moisture in insulation.

The LTES is performing as expected regarding main KPIs (energy balance, efficiency…).

2.3 BTES case study

1. PROJECT ID: EMMABODA (SWEDEN)

Type of usage: seasonal storage of heat
Year commissioned: 2010
Main heat source: Industrial waste heat
Owner: Xylem Water Solutions AB
Technical details: Boreholes configurations: 140 boreholes of 150 m depth
Underground volume: 336’000 m³
Storage capacity: 3’800 MWh (for a ΔT of 20°C)
Storage temperature: 60-40°C (design), 40-20°C (actual)

2. MODELLING AND SIZING

Historic energy data was available in the control system and used for the design of the BTES. Only the BTES technology was considered for this project.

Based on a couple of Thermal Response Tests in two exploration boreholes the thermal parameters of the rock were evaluated and used for simulation in a model named DST. The DST simulation results were used for design of number of boreholes, the depth, and distance between the holes.

3. STORAGE MATERIALS

As borehole heat exchangers a thermal resistant plastic was used (PPE) that could withstand temperatures up to +80ºC.

4. LAND

For land selection, a grass field area inside the industrial property was chosen as the only possible alternative.

5. PERMITTING PROCESS

A minor environmental risk analysis was sent to local and regional authorities according to Swedish regulations. No objections were received from their side.

6. CONTRACTUAL SCHEME

Xylem Water Solutions Ab is the owner, the operator, and the heat user of the BTES.

7. TENDERING PROCESS

There were tenders for two external contracts (1) the drilling of boreholes and (2) fabrication and installation of borehole heat exchangers and connection pipes.

8. CONSTRUCTION

The weather conditions did affect the construction work, as the boreholes were drilled in the harsh winter 2009-10, that was slowing down the performance and increased the cost by some 15 %.

9. OPERATION & MAINTENANCE

The BTES was instrumented for control purposes, no additional measurement was added to further assess its performance. The instrumentation works properly.

No heavy maintenance activities are planned, but some unexpected maintenance activities had to be conducted at the early days of operation: the circulation pump was replaced, the heat exchanger was cleaned, and an additional gas separator had to be installed.

The BTES has been performing as expected regarding main KPIs (energy balance, efficiency…) for the last five years.

2.4 ATES case study

1. PROJECT ID: MIDDENMEER (NETHERLANDS)

Type of usage: seasonal storage of heat
Year commissioned: 2021
Main heat source: geothermal heat of 90 °C from 2’400 m
Owner: Ennatuurlijk Aardwarmte
Technical details: Average water volume: 440’000 m³ Average energy stored: 28 GWh
Charge-discharge capacity: 12-10 MW_{th}
1 cycle of charge/discharge per year
Max operational temperature: 90°C (infiltration temperature)
Maximum allowed storage volume: 600’000 m³ groundwater (38 GWh capacity)
Maximum allowed extraction: 700’000 m³ of groundwater
Thickness of aquifer: 20 m
Distance between wells: 220 m
Storage aquifer depth: 385 m

2. MODELLING AND SIZING

The data for heat delivery (heat load curves, weather, DHN integration points, etc.) were not easy to acquire, as part of the delivery system already existed, and another part had yet to be designed at the same time. The data for heat storage were readily available, but unforeseen external factors influenced the initial real world storage capability.

The ATES technology was chosen because a large seasonal storage was desired for increased use of geothermal heat. Additionally, the soil composition was suitable for that. Besides, there was already a TTES on the site for daily cycle storage.

HST and Matlab modelling tools were used to design the ATES. Matlab was used for various custom calculations, including FEM[5] thermal modelling of heat conduction and simulating flow with a complex custom-made injection system.

3. STORAGE MATERIALS

The following materials were selected for the storage construction:

- Glass-fiber Reinforced Epoxy (GRE):
  - Straight tubing and large radii,
  - Corrosion resistant,
  - High pressures possible,
  - Resists temperatures up to 120°C,
  - Smoother than stainless steels (less hydraulic losses),
  - Lower heat conduction than metals.
- Stainless steel 316L:
  - Based on specifications, corrosion resistant up to present levels of salinity and applied temperatures,
  - Shorter bends possible than GRE,
  - Easier for strength calculations than composite materials.
- Titanium plate heat exchangers provide more certainty for corrosion resistance than SS 316L.

4. LAND

The land was selected because of the presence of underground aquifers with vertically limited groundwater dispersion. 6 m² of outside floor area is needed per well. The technical room with heat exchangers, electrical components, filtering, monitoring, and water treatment requires roughly 1,5 m² for each 1 m³/h of flow. So, if maximum flow is 100 m³/h the necessary area is roughly 150 m². When the technical room includes heat pumps for high temperature delivery (65°C and above), the required floor area will be roughly double that of the technical installation without heat pumps.

For this project, land is privately owned. There were no issues with the selected land, but if soil is contaminated, it needs to be collected and disposed of at an appropriate facility.

[5] Finite Element Method

5. PERMITTING PROCESS

No urbanistic rules compliance applies to existing systems in the Netherlands, but such rules may be applicable for future projects.

Significant heat leaks to higher groundwater layers could induce a risk for the environment (bacteria growth), so this aspect must be monitored. No risk for people is identified, except while building the system and while doing large maintenance with cranes. Local acceptance is an issue to be considered. For instance, it is important to inform people in the neighbourhood that there is no risk of seismicity. Besides, the well housing can be up to 3 meters tall, so these may stand out in urban areas.

6. CONTRACTUAL SCHEME

The energy provider is the owner and the operator of the ATES. It was responsible for building the technical room and remains in charge of heat storage, heat delivery and maintenance to the system. The contractor dug the wells and corresponding piping and is now responsible for the maintenance of the wells. An engineering consultancy firm monitors the groundwater system and gives advice on performance improvements. They also execute groundwater tests to determine the effects of heating on the groundwater composition. The heat user can give inputs about the required energy for its needs and is committed to consume a minimum amount of heat while the system is active.

7. CONSTRUCTION

Weather conditions did not affect the construction work. During commissioning, all systems were extensively tested. It took two weeks of collaboration between producers of subsystems, owner of the system, user of the system and engineering firm.

8. OPERATION & MAINTENANCE

The LTES and its instrumentation system is performing as expected. A lot of effort was put into adding monitoring possibilities to the system to determine its technical and energy performance.

Regular maintenance of wells is planned twice a year: it consists in visual inspection of the wells, measurement of hydraulic performance and electrical resistance of the pump. No unexpected maintenance activities had to be conducted so far.

KEY PERFORMANCE INDICATORS: TYPES, SCOPE, AND MAIN INDICATORS.

As introduced previously, key performance indicators (KPIs) are necessary at every stage of an LTES project to evaluate all its aspects. KPIs can be used in all project phases:

- During the opportunity phase, they are used to preselect the most relevant LTES technology and set a rough sizing based on the initial techno-economic studies at a system level.
- During the design phase, they are used to finalize the technology choice and sizing realized in the previous phase. Additionally, KPIs are used to calculate the expected performance and the target price at the storage level.
- During the tender phase, they are used to select the best product and supplier on a techno-economic level and set a clear contract between the project owner and the suppliers regarding price, durability, and performance.
- During the implementation phase, technical KPIs are used to conduct the storage commissioning through performance checks. During the operation phase, they are used for supervising the storage operation, performance inspection, and fault detection.

There are many different indicators that can be used to conduct the activities mentioned previously. A comprehensive list has been built to define the main indicators used and is available in Appendix 1: KPIs list. This section will introduce the different categories of indicators, their definition, and their use. It should be noted that a paper has thoroughly investigated some parameters to compare the performance of two PTES and is used as a reference for some of the indicators introduced in this part (Sifnaios, I., Jensen, A.R., Furbo, S., Fan, J., 2022).

1. Different indicator types

1.1 KDP vs KPI

The term indicator is quite broad and can be used to describe many different things. Thus, in the context of this work, a distinction has been made between two terms:

- Key design parameters (KDP) are defined as a value that can be obtained before implementing the storage. Those are theoretical figures mainly used for the design and sizing of the LTES, such as the volume, the land area required or the storage capacity.
- Key performance indicators (KPI) are defined as a value that can only be obtained after implementation, meaning that they require the storage to be operated to be calculated. Those are monitoring data that are mainly used for characterizing the performance of the LTES, such as charged and discharge energies, energy efficiency or the heat supply tariff to the DHN consumers.

1.2 KPI types

A second distinction has been created between indicators based on their types. The three categories identified are Technical, Economic, and Environmental. This Task did not only focus on technical parameters, which are usually the first in mind. As it aimed to give guidelines for LTES project developments, it included the economic and environmental indicators, which are crucial for a more holistic perspective.

The technical indicators have a very broad scope as they can be used to assess the performance of the entire district heating system but also of a specific storage component. Thus, it is essential to define the boundaries in which these indicators are used in this task. This is done in the following chapter.

The economic indicators are crucial for any party participating in project development as they are the drivers of the feasibility of the project. All the actors impacted by the LTES have a strong interest in its influence on the system's economy. For example, the district heating customer is interested in the impact on the heat cost. At the same time, the project developer can use the fossil heat price threshold from which the addition of a storage allows a weighted marginal cost balance to promote the interest of its solution. The decision-makers assess the project relevancy based on a combination of technical and economic indicators: the techno-economic feasibility.

The final category of indicators is the environmental, which is crucial during the design and operation phases. The impact of an LTES project is not negligible for its surrounding environment; thus, regulations apply to the potential harmful effects it could generate. Reliable monitoring of environmental indicators helps provide transparency on the topic and builds trust with the local community and the corresponding authorities.

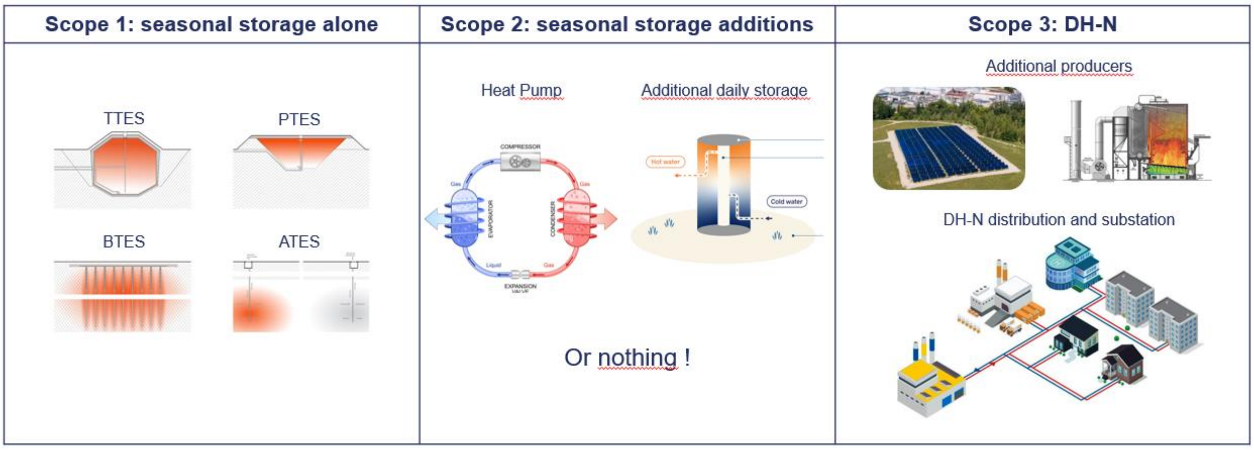

Figure 8: Scopes considered for indicators boundaries.

1.3 System boundaries

Finally, the indicators can be distinguished based on their scope. This distinction is essential when considering energetic KPIs. For example, most BTES projects are combined with a heat pump to raise the temperature of the discharged flow to an acceptable level for the district heating delivery. Thus, when assessing this type of system, the additional components should be part of the scope considered to calculate relevant indicators, especially regarding energy balance, but also for economic considerations.

The first scope is confined to the boundaries of the storage; the second one includes the additions to the storage (defined as additional equipment contributing to the storage service, e.g., heat pumps), and the third includes the whole DHN system.

Depending on the actor considered, they focus on different scopes regarding their involvement in the project. The work package contractors have a stronger focus on the first scope, while the DHN operators have a great interest in the third scope.

1.4 List of indicators

During this task, a list of indicators was created and is available in Appendix 1: KPIs list. It tackles the main indicators that one should consider during project development. The following part will provide recommendations regarding the use of those indicators.

The previous categories are differentiated in the list, and the following table sums up the number of indicators per category:

Table 1: Indicators categories.

	Storage alone	Storage system	DH Network
Key Design Parameter	14	0	4
Technical KPI	20	1	3
Economic KPI	6		2
Environmental KPI	8		

2. Definition and formula of main LTES indicators.

2.1 Energy balance: charged/discharged energy, internal energy variation, losses.

The first technical indicators considered at a project level are the ones constituting the energy balance. The combination of charged (E_{cha}) and discharged (E_{dis}) energy provides a first glimpse during the opportunity phase, and those indicators are followed through the project, as they constitute the basis of the service delivered to the DHN and its economy.

$$E_{cha} = \int_{start}^{end} \dot{m}_{cha} * C_{p_{mean}} (T_{in} - T_{out})\, dt \tag{1}$$

$$E_{dis} = \int_{start}^{end} \dot{m}_{dis} * C_{p_{mean}} (T_{out} - T_{in})\, dt \tag{2}$$

Where:

- $\dot{m}_{cha}$ and $\dot{m}_{dis}$ are the charged or discharged mass flows through the storage.
- $C_{p_{mean}}$ is the mean specific heat capacity of the medium (can be calculated for the average temperature between T_{in} and T_{out}).
- T_{in} and T_{out} are the respective temperatures of the flow going in and out of the storage.

The internal energy change (ΔE_{st}) is an important indicator to calculate accurately the energy balance and energy efficiency of an LTES. Since most LTES are operated as seasonal storages, the storage energy content at the beginning and the end could be very different if the investigated period spans between summer and winter, for example. This indicator is used to balance the impact of this content change when calculating some KPIs.

$$\Delta E_{st} = \sum_{l=1}^{N_s} V_l * \rho\left(T_{l_{mean}}\right) * C_p\left(T_{l_{mean}}\right) * \left(T_{l_{end}} - T_{l_{start}}\right) \tag{3}$$

Where:

- N_s is the number of temperature sensors in the storage. For each sensor, a layer (l) is considered from the half-distance to the upper sensor, to the half-distance to the lower sensor, V_l being the resulting volume.
- $T_{l_{start}}$ and $T_{l_{end}}$ are the temperatures measured by the given sensor at the start and end of the period considered, respectively.
- $C_p(T_{l_{mean}})$ and $\rho(T_{l_{mean}})$ are the specific heat capacity and density of the volume, respectively. They are considered at $T_{l_{mean}}$, mean value between $T_{l_{start}}$ and $T_{l_{end}}$.

The losses of the storage to the environment are difficult to measure in practice. Usually, the heat losses to the ambient through the top insulation can be measured using heat flux sensors. However, it is hard to estimate the heat losses toward the ground. To overcome this difficulty, the total heat loss (toward the ambient and soil) can be calculated using the storage energy balance:

$$E_{loss} = E_{cha} - E_{dis} - \Delta E_{st} \tag{4}$$

The energy balance is fundamental for calculating energy efficiency, which is the most commonly used indicator for assessing the performance of a storage. However, energy efficiency is highly influenced by the operating conditions of the storage. Two expressions of energy efficiency were introduced in Sifnaios' paper depending on the attribution of internal energy change to the charged or discharged energy. The authors recommended using the $\eta_{E,1}$ expression. The reason is that it accounts better for the existing energy content of the storage. For example, if there is existing energy in the storage from the previous cycle, less energy has to be charged.

$$\eta_{E,1} = \frac{E_{dis}}{E_{cha} - \Delta E_{st}} \tag{5}$$

$$\eta_{E,2} = \frac{E_{dis} + \Delta E_{st}}{E_{cha}} \tag{6}$$

Exergy is an indicator that measures energy quality; following the previous definition of energy efficiency, a definition proposal for exergy efficiency is introduced:

$$\eta_X = \frac{Ex_{dis}}{Ex_{cha} - \Delta Ex_{st}} \tag{7}$$

Where Ex_{cha}, Ex_{dis} and ΔEx_{st} are the respective charged, discharged and internal variation of exergy.

This indicator has been defined in previous scientific publications (e.g., Rosen, 1999), however, it mainly tackled daily storages. Similarly, as the definition of energy efficiency, when it comes to seasonal storages the variation of exergy content within the storage must be taken into account so that the indicator provides relevant values.

2.2 Capacity,number of cycles

As mentioned previously, the number of cycles has a major influence on the performance of the storage and on the values of other indicators. This indicator corresponds to the amount of heat discharged from the storage compared to its maximum capacity over a year, thus giving information about the use of the storage.

To define this indicator, the storage capacity is introduced as:

$$Q_{st} = V * \rho * C_p * (T_{max} - T_{min}) \tag{7}$$

Where T_{max} and T_{min} are the respective design maximum and minimum temperatures of the storage. Those temperatures are reference temperatures introduced in the design phase based on the expected temperature range at this stage. When comparing measurements for several years of operation, one could use the minimal and maximal temperatures measured within the storage across the period, thus using the same capacity for all years.

This highlights the need for further common guidelines and definitions for these KPIs to allow a fair comparison of the LTES performances.

The number of heat storage cycles results in:

$$N_C = \frac{E_{dis,yr}}{Q_{st}} \tag{8}$$

In the literature, the value considered for Q_{st} can either be the KDP or the KPI. Both present disadvantages; as a KDP, there is a need for defining reference temperatures that can differ from what really happens; as a KPI, its value changes from one year to the other, as the maximum and minimum temperature reached are not always the same, thus it less relevant for comparing different years for the same storage. This example shows that further work is needed to agree on definitions for basic KPIs such as the storage capacity.

As explained previously, it can be used to define whether a storage is used for seasonal or short-term operations. A storage with approximately 1 cycle per year is used for a seasonal application. But LTES used as short-term storages can have a higher number of cycles. For example, Høje Taastrup PTES is used as a bi-weekly storage for district heating and is completely charged and discharged on a bi-weekly basis. Usually, a storage used for short-term operation will have a higher amount of discharged energy compared to a seasonal. Thus, from equations 6 and 8, it is obvious that this would also lead to more storage cycles and a higher efficiency. Therefore, those indicators shall be considered together when assessing the performance of the LTES. This is one of the illustrations of the impact of the operating conditions of a storage over its KPIs and the importance of accounting for the greater picture when comparing two projects.

2.3 Stratification indicators

This category of indicators is mainly applicable to storages relying on vertical thermal stratification such as PTES and TTES. BTES systems rely on horizontal stratification; thus, one could try to extrapolate these indicators for this technology, but this was not investigated in this report. Ensuring high degree of stratification in thermal energy storages is crucial to reaching their full potential. Indicators providing insights about stratification within the storage will be introduced hereafter (Sifnaios, I., Jensen, A.R., Furbo, S., Fan, J., 2022). They are formulated assuming that a water storage is divided into layers around temperature sensors distributed along its depth.

The MIX number assesses the storage stratification on a scale from perfectly stratified to fully mixed. Its definition, given in the KPI list, leads to a value of 0 in the first case and 1 in the latter. It is calculated based on the moment of energy (M_E) as follows:

$$MIX = \frac{M_E^{strat} - M_E^{actual}}{M_E^{strat} - M_E^{mixed}} \tag{9}$$

The momentum of energy of each tank is calculated so that they have the same energy content as the tank investigated. It is calculated based on the properties of the fluid, the volume of each layer i, its distance to the bottom of the storage z_i and a reference temperature T_{ref}, as follows.

$$M_E = \sum_{i=1}^{N} \rho_i * V_i * C_{p,i} * \left(T_i - T_{ref}\right) * z_i \tag{10}$$

The stratification coefficient is defined using the mass and temperature of each layer m_i and T_i, the weighted average temperature of the storage T_{avg} and its total mass m_{tot}.

$$St = \sum_{i=1}^{N} \frac{m_i * (T_i - T_{avg})^2}{m_{tot}} \tag{11}$$

The last stratification indicator recommended by Sifnaios et al. is the exergy destruction (normalized with the storage volume) based on the exergy balance of the storage. The main advantage of this indicator is that it accounts for the exergy lost due to the heat losses, which allows for the comparison of the stratification of two storages with different heat losses. This is important, as the previously mentioned stratification indicators tend to show storages with low heat losses as well-stratified.

$$\Delta Ex_{destr,norm} = \frac{\Delta Ex_{flow} - \Delta Ex_{store} - \Delta Ex_{loss}}{V} \tag{12}$$

In order to calculate the terms of the exergy balance (i.e., flow, store, loss), the following formula was used. Where ΔH is the change in enthalpy, ΔS is the change in entropy, and T_0, the dead state temperature.

$$\Delta Ex = \Delta H - T_0 * \Delta S \tag{13}$$

Another indicator, also defined in the KPI list, is the Figure of Merit, which basically reflects the temperature level at the outlet of the LTES during discharge.

All these stratification indicators can be used to investigate the quality of thermal stratification of the storage. However, they can be challenging to calculate since they require information like the temperature profile in the storage, charged/discharged energy, storage geometry, etc. Thus, they are usually used only if a deeper understanding of the storage performance is required.

2.4 Main economic indicators

The economic aspect is one of the key drivers of project development; thus, it is necessary to use consistent economic indicators at every stage of the project. The economic indicators used vary depending on the role of the project actor. The indicators introduced hereafter tackle different boundaries, some focus directly on the storage itself but others show the influence of the component on the entire DHN.

First, the CAPEX (capital expenditures) and OPEX (operation expenditures) of each component are at the center of the economic considerations of the project. The combination of the costs of all components enables the project owner to estimate the costs of the storage project.

Considering the costs presented above, the DHN operator can estimate the DHN weighted marginal heat price with or without LTES. This indicator provides information about the economic interest of the storage. It is a decisive indicator in the early stages of the project (when considering the first scenarios and sizing) and provides a first estimation of the project's feasibility. Similar information can be obtained from the fossil heat price threshold, where the addition of storage allows for a weighted marginal cost balance. However, this indicator gives information based on fossil heat prices, which can be highly volatile.

Finally, the economic indicator that impacts the consumer and is derived from the ones presented above is the increase or reduction in heat supply tariff when including the storage in the district heating. This indicator can directly influence the social acceptance of the project.

2.5 Main environmental indicators

As part of the project development, it is necessary to carry out environmental impact assessments and address the necessary permits. Depending on the regulation and country, the environmental study can vary in content and exhaustiveness. The common topics investigated in these studies are the impact on people, fauna, flora, landscape, soil content, groundwater, and local pollution.

A major part of these assessments can be answered through visual inspection or yes/no questions, but measurements or simulations can also be required. The main indicators are linked to the influence of the storage on the underground. The reason is that this influence cannot be monitored visually and usually evolves throughout the project. The level of requirement and the methodology to assess those indicators may vary a lot from one case to the other, but the main topics to monitor are the following:

- Effects on the underground fauna,
- Effects on groundwater (chemistry, temperature, and quality),
- Extent of the heating zone and temperature in the surrounding soil.

These assessments and monitoring ensure compliance with regulations and avoid a negative impact of the storage on the local community.

EXAMPLE CASE OF KPI USE FOR TYPICAL LTES APPLICATIONS.

- Newheat internal studies exploring main KPI sensitivity to project type and design parameters.
- Highlights the interest (or not) of several KPIs in several situations and is used for recommendation of standard indicators.

Some KPIs described in the previous section will be calculated and discussed in two LTES case studies: first with a TTES coupled to a flat plate solar thermal collector field for an industrial application (malthouse), and then with a PTES coupled to a District heating Network. The TTES is used for daily storage while the PTES is implemented for seasonal storage, but both are considered as LTES based on the criteria expressed in the introduction. The aim of this study is to assess the influence of operating strategies (on the TTES case) and design parameters (on the PTES case) on the performance of the storage systems and to determine whether this influence can be clearly and fairly observed on some KPI values. In other words, this work aims at checking 1) if the KPIs can be calculated in a clear and univocal way and 2) which of the selected KPIs are relevant to assess the performance of an LTES or can be used as a performance guarantee.

1. TTES case study

In this section, the technical performances of a TTES will be assessed. The considered system is a 3000 m^3 TTES, which is part of a solar thermal plant composed of a 14'250 m^2 solar field and designed to heat moist air for a malthouse process through a water-air finned tube heat exchanger. The main characteristics of the solar field and storage tank are gathered in the Table below.

Table 2: Main design parameters of the considered solar thermal system with TTES.

Solar field	
Gross collector area	14 248 m^2
Collector type	Savo-Solar SF500-15 SG
Heat transfer fluid	Propylenglycol -20
Storage	
Storage medium	Water
Storage type	TTES
Volume	3 000 m^3

This plant is simulated with Newheat's internal tool called DYNAMHEAT, which is an Excel/VBA tool used for techno-economical evaluation of renewable heat plant projects at different stages (pre-feasibility, design, operation…). It was developed for low temperature multi energy large-scale heat production plants design and simulation and was validated against real plants operational data. The methodology used is dynamic thermo-hydraulic modelling on an hourly basis, including:

- Geometrical, optical, and thermal performance calculations in the solar field and piping,
- Idealized hydraulic calculations (based on minimum and maximum flowrate for collector rows),
- Multiple producers (including heat pumps) & process integration points,
- Storage (TTES or PTES) based on a stratified model with multiple integration points.

The modelling approach for storage is a multi-node model solving the following equation for each layer:

$$\rho \cdot C_p \cdot S \cdot \frac{dT(t,x)}{dt} + \dot{m} \cdot C_p \cdot \frac{dT(t,x)}{dx} = \varepsilon \cdot S \cdot \frac{d^2T(t,x)}{dx^2} + U \cdot P \cdot \left(T_{amb}(t) - T(t)\right)$$

With T(t,x) being the temperature of the storage layer at depth x, ρ the fluid density, C_p its specific heat, $\dot{m}$ the fluid mass flow through the considered volume, ε the equivalent thermal conductivity through the considered section (between storage and environment) S, U the coefficient of thermal losses, P the perimeter of the tank, and T_{amb} the ambient temperature.

The temperature inversion (when a lower layer is hotter than a higher layer) is considered by mixing concerned volumes. The main output of this tool is the annual heat production (MWh_{th}/yr) for a given plant configuration, sizing, and operating mode. Moreover, it allows extracting a wide selection of KPIs (overheating fraction, LCoH, Return on Investment, energy balances…) from the system but also ones more specific to the storage: charged/discharged energy, losses, temperatures within the storage.

The aim of this case study is to assess the influence of the operating modes used to charge and discharge the storage system. On one hand, the solar field can be operated in "production" preheating or heating mode:

- in preheating mode, the solar loop design mass flow is sent to the solar heat exchanger whatever the temperature is at the outlet of the solar field,
- in heating mode, the solar loop mass flow is controlled to reach a setpoint temperature high enough to satisfy the temperature setpoint of the industrial process.

On the other hand, similarly, the heat stored in the storage system can be sent to the process using "supply" preheating or heating mode:

- in preheating mode, the process loop design mass flow is sent to the process heat exchanger as soon as the outlet temperature of the storage tank is higher than that of the return flow at the bottom,
- in heating mode, the process loop mass flow is controlled to reach a setpoint temperature able to satisfy the temperature setpoint of the industrial process.

To quantify the influence of the operating mode on the performance of the storage system on an annual basis, many KPIs can be used (energy efficiency, thermal losses, seasonal energy efficiency, exergy efficiency, number of cycles…). In this study, we will focus on the number of heat storage cycles, energy, and exergy efficiency. The table below shows the calculated values of these KPIs for three considered operating modes.

Table 3: Energy balances for several operating modes.

Production mode	Heating mode	Heating mode	Preheating mode
Supply mode	Heating mode	Preheating mode	Preheating mode
Annual production	5860 MWh/yr	7198 MWh/yr	8129 MWh/yr
Share of the total heat demand	22.5%	28.5%	32.2%
Number of cycles (per year)	26	34	38
Energy efficiency	97%	98.6%	98.6%
Exergy efficiency	97%[6]	83.4%	90.7%

The number of cycles is an interesting indicator of the operational conditions. If the reference storage capacity is considered constant from one year to another, it is strictly proportional to the discharged energy. In this study the number of cycles is relatively low for storage systems used on a daily basis, which shows that only a small fraction of the tank storage capacity is used every day. The reference temperatures used were chosen based on the storage's expected temperature range and are the same for all operating modes in order to allow a fair comparison of the number of cycles.

Energy efficiency values are very high and similar for all operating modes, as expected for storage systems with daily use: annual discharged thermal energy is far higher than thermal losses. Energy efficiency is slightly higher when supply is operated in preheating mode, because a larger amount of heat can be valorized from the storage tank.

On the contrary, exergy efficiency varies a lot according to the selected operating modes. When the storage is charged in heating production mode, a better KPI is reached in heating supply mode. This can be clearly interpreted by the fact that in heating supply mode the storage tank is discharged only if it can provide a "high quality" thermal energy, in other words with temperature levels complying with the heat demand.

However, when preheating supply mode is considered, operating the solar field in preheating production mode (and thus charging storage with variable temperatures) leads to higher exergy efficiency. This is because globally the temperature level of the discharged heat is less deteriorated than if the storage is charged with constant high temperature.

This study shows that for such daily storage systems, operating modes have more impact on exergy efficiency than on energy efficiency. However, the supply operating mode is generally imposed by the heat user, this is not a strategy that is defined by the operator. For users requiring supply in preheating mode, this study shows that both exergy efficiency KPI and annual heat production are higher when the solar heat production is operated in preheating mode. This result may seem obvious in the case of a unique heat producer, but much less direct for systems with multiple producers and multiple users.

[6] In this scenario, the exergetic degradation is very low and the model is not able to represent it, which explains the same value for both efficiencies.

For such complex systems, the exergy efficiency may be an interesting KPI to optimize the operation of the storage system.

2. PTES case study

In this section, the technical performances of a PTES are assessed. The considered system is a 430 000 m^3 PTES, connected to a District Heating Network, operated under fixed inlet temperature conditions. The main characteristics of the storage tank and operating conditions are gathered in the Table below.

Table 4: Main design parameters and operating conditions of the considered PTES system.

Storage design	
Volume	430 000 m^3
Depth	25 m
Slope	26.7°
Operating conditions	
Charging temperature	90°C
Return cold temperature	32°C
Annual charged energy	29.1 GWh

This system is modeled in Modelica language, which is an object-oriented language used especially for complex multi-domain systems modelling. It is an equation-based, acausal and object-oriented modelling language, which facilitates reuse of pre-existing classes. Only a few models have been developed for PTES in Modelica, none being validated and available open-source or commercially. Dahash et al. validated a model before studying some key parameters on LCOS (Dahash, A., Ochs, F., and Tosatto, A., 2020). Reisenbichler et al. also created a model following a similar approach. It was compared to existing TRNSYS models for validation purposes (Reisenbichler, M. et al., 2021). Finally, an open-source library for modelling underground thermal energy storage systems has been developed (MoSDH) (Formhals, May 2020). This open-source library served as inspiration for the PTES model used in this work.

The water region is represented by a thermally stratified tank component. The PTES, which has a reverse truncated-pyramid shape, is simplified to a cylindrical shape to reduce the computational time. The model (described in (Fournier, N. et al., 2023)) is derived from a tank storage model which is discretized in layers along the depth of the storage. In order to account for the actual geometry of a PTES, the heat loss term through a face of the storage has been adapted by considering the area of this face as if it was a corresponding truncated pyramid. The soil region is developed based on the global model technique from MoSDH library. It meshes the soil in two dimensions (radial and axial), following an axial symmetry simplification.

Finally, the top boundary conditions have been defined considering a convective heat flux at the surface of the PTES, with a prescribed ambient temperature at the top boundary, adiabatic conditions at the inner boundary due to symmetry, and outer and bottom boundaries represented with the undisturbed Soil Temperature Model from the Buildings library (Wetter, 2014).
To include a PTES system in its District Heating network, the operator may require a performance guarantee from the PTES project developer. This performance guarantee necessarily includes a sound technical KPI, and the storage energy efficiency seems to be a reasonable option. To assess the

sensitivity of this KPI on some critical design parameters, a sensitivity analysis was conducted on two categories of parameters:

- Those which can vary over time (random or degradable): ambient temperature and lid conductivity,
- Those which are uncertain at the first stages of the project: soil characteristics (thermal conductivity and capacity).

For each of those parameters, a range is estimated from a reference to a worse case, based on literature and information from suppliers, creating several scenarios. Five-years simulations are conducted for each scenario. Table 2 shows the energy balance and efficiency of the storage for the second year (after one year of preheating), for three scenarios with conservative parameters regarding PTES performance. It shows that the KPIs can vary significantly due to uncertainty or potential degradation of several parameters.

Table 5: Energy balances for several sets of parameters.

Scenario	Reference	Unfavourable soil	Unfavourable soil & lid
Lid U-value (W/(m².K))	0.17	0.17	0.20
Soil thermal conductivity (W/(m.K))	2.5	5.1	5.1
Soil specific heat (J/(kg.K))	1000	1400	1400
Energy efficiency (η_1)	83.0%	78.4%	76.9%
Energy efficiency (η_2)	83.4%	79.1%	77.6%

This study shows that design technical parameters have a significant influence on the energy performance of the PTES. Consequently, a special attention should be paid to the characterization of these parameters, in particular those concerning soil characteristics and lid thermal performance, in order to lower the economic risk of a PTES project.

3. Conclusions and perspectives

This study showed the relevance of well-defined KPI (notably exergy and energy efficiencies) for the analysis of the performances of LTES. On 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 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.

A further step will be to propose guidelines on the test procedures to quantify these indicators from simulations results or measured data. Without guidelines, various kinds of protocols can be followed, often leading to different values for the indicators. Thus, there is a strong need to ensure that indicators are estimated in a systematic and reproducible way. The development of such guidelines is included in the program of the follow-up IEA ES task and will be a sound basis for performance checks standards. Moreover, a detailed investigations of all the indicators mentioned can lead to a better understanding and thus recommendations for their use for contractual performance guarantees.

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APPENDIX 1: KPIS LIST

The following list presents the main key performance indicators used for LTES gathered in Task 39. Some of them are defined more thoroughly in this report and the full list is made available on Task 39 website.

KPI	Description	Unit	Reference
MIX number	Quantifies the temperature distribution inside the storage	-	(Sifnaios, I., Jensen, A.R., Furbo, S., Fan, J., 2022)
Figure of Merit	Quantifies the losses within the storage due to losses to the ambient and destratification	-	
Exergy yield	Quantifies the usability of the stored energy	-	
Exergy efficiency	Quantifies the storage efficiency regarding its energy quality	%	(Sifnaios, I., Jensen, A.R., Furbo, S., Fan, J., 2022)
Stratification coefficient	Quantifies the stratification based on the deviation of the storage temperature profile to its mean temperature	K^2	(Sifnaios, I., Jensen, A.R., Furbo, S., Fan, J., 2022)
Exergy destruction	Exergy destroyed within the storage (excluding heat losses)	MJ/m^3	(Sifnaios, I., Jensen, A.R., Furbo, S., Fan, J., 2022)
Min/max temperature for the discharge	Dischargeable temperature range from the storage	K	(Yang, T., Liu, W., Kramer, G. J., Sun, Q., 2021)
Min/max return temperature	Return temperature range from the storage	K	
Charged heat	Heat charged over a period	GWh	(Pan, X., Xiang, Y., Gao, M., Fan, J., Furbo, S., Wang, D., Xu, C., 2022)
Discharged heat	Heat discharged over a period	GWh	(Pan, X., Xiang, Y., Gao, M., Fan, J., Furbo, S., Wang, D., Xu, C., 2022)
Internal energy change	Energy variation within the storage between the end and the start of a period	GWh	(Pan, X., Xiang, Y., Gao, M., Fan, J., Furbo, S., Wang, D., Xu, C., 2022)

Storage losses	Heat lost by the storage over a period	GWh	(Pan, X., Xiang, Y., Gao, M., Fan, J., Furbo, S., Wang, D., Xu, C., 2022)
Energy efficiency	Overall energy efficiency of the storage	%	(Sifnaios, I., Jensen, A.R., Furbo, S., Fan, J., 2022)
Seasonal energy efficiency	Seasonal efficiency quantifies the efficiency of the storage system as if it was solely used for seasonal heat storage	%	(Sifnaios, I., Jensen, A.R., Furbo, S., Fan, J., 2022)
Number of heat storage cycles per year	Yearly heat discharged regarding storage capacity	1/yr	(Yang, T., Liu, W., Kramer, G. J., Sun, Q., 2021)
Number of volume storage cycles per year	Yearly volume discharged regarding storage volume	1/yr	
Storage period	Heat storage cycles period	yr	(Yang, T., Liu, W., Kramer, G. J., Sun, Q., 2021)
Annual refill volume	Volume of water refilled in the storage per year	m^3/yr	
Specific flow rate	Indication of clogging in subsurface wells, specific to ATES	m^3/h/m	
Auxiliary power consumption	Electrical power consumption of the auxiliary devices needed to operate the TES system if any	W	
LCOES	Levelized Cost of Energy Stored	€/kWh	
Initial investment (CAPEX)	CAPEX of the project, refined gradually through the stages - Include Technical and non-technical CAPEX	€	(Yang, T., Liu, W., Kramer, G. J., Sun, Q., 2021)
Specific CAPEX	Storage CAPEX per volume unit	€/m^3	(Yang, T., Liu, W., Kramer, G. J., Sun, Q., 2021)
Annual OPEX	OPEX of the project, refined gradually through the stages - Include Technical and non-technical OPEX	€/year	

Energy specific OPEX	**Storage OPEX per energy charged/discharged**	**€/MWh/year**	
Heat source energy fractions with or without LTES	Yearly energy production by each DHN producer, before and after storage integration	%	
Heat source power fractions with or without LTES	Peak power of each DHN producer, before and after storage integration	%	
Reduction of peak load in DHN	Potential of peak load reduction thanks to storage use	MW or %	
Energy specific CO2 emissions with or without LTES		tCO2/MWh	
Fossil heat price threshold from which the addition of a storage allows a weighted marginal cost balance		€/kWh	
DHN weighted marginal heat cost with or without LTES	Comparison of DHN weighted marginal heat cost before and after LTES addition	€/kWh	
Hydrogeological effects: groundwater flow related to changes in the hydrologic equilibrium			(HEATSTORE, 2021)
Flow around the wells, mixing of water and corresponding changes in groundwater quality			(HEATSTORE, 2021)
Reservoir thermal effects and extent of heating zone (power exchanged with underground, temperature in the surrounding soil)			(HEATSTORE, 2021)

Soil mechanic effects related to changes in hydraulic head and to thermal expansion or shrinkage			(HEATSTORE, 2021)
Changes in physical properties of the aquifer due to temperature changes			(HEATSTORE, 2021)
Changes in groundwater chemistry and quality related to temperature changes, and the corresponding risks for pollution			(HEATSTORE, 2021)
Changes in microbial populations related to temperature changes.			(HEATSTORE, 2021)