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Demonstrating large pit thermal energy storages and improving their components, processes, and procedures for an accelerated realisation of 100% sustainable district heating networks in Europe.

TREASURE

Guidelines on modelling and simulation

Recommendations for system analysis of large thermal energy storage integration concepts

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Prepared By:	Carles Ribas Tugores
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Contribution and Revision By:	Andreas Hawel Geoffroy Gauthier Jon Børgesen Matthias Leitner Maria Moser Meng Gao Nathan Fournier Thomas Schmidt

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Terms, definitions and abbreviated terms

CAPEX	Capital expenditures
DH	District heating
DHN	District heating network
ES	Energy storage
GA	Grant agreement
IEA	International energy agency
KPI	Key performance indicator
LCOH	Levelized cost of heat
LTES	Large thermal energy storage[1]
OPEX	Operational expenditures
TCP	Technology collaboration programme
TES	Thermal energy storage

[1] A large thermal energy storage is defined in IEA-ES Task 39 as a sensible thermal energy storage (no phase change), designed to store at least 1 GWh of heat per year at atmospheric pressure (no pressurized system). The stored heat should be suitable for discharge into DHN, at temperatures higher than 50°C (see https://iea-es.org/task-39/wp-content/uploads/sites/21/IEA-ES_Task39_WPA_Deliverable_A0a_Task_brochure%E2%80%93Introduction.pdf)

1. Introduction

District heating systems are traditionally designed following a static approach[2,3] (e.g. carry out an analysis of the status quo (actual and future heat demand, i.e. obtention of load duration curve, etc.), heat distribution and heat generation design based on peak loads, and full load operating hours, design temperatures, etc). While the static approach might suffice for designing traditional DH systems that are able to provide heat on demand, the integration volatile energy sources with high heat capacities (e.g. solar thermal) and thermal energy storage (TES) do require a more sophisticated approach to be able to consider their dynamics[4]. In this regard, dynamics systems are typically studied trough simulation. These simulations are not only relevant because allow an accurate representation of the real system behaviour but because allow analysis of expected performance of a system prior to construction, which is a key aspect for LTES system integration concepts as there is limited experience due to a limited number of systems and the singularity of the projects. In this context, the role of modelling and simulation has a key role in understanding and optimizing a LTES system. It offers several advantages of the model-based systems engineering[5] (MBSE), the most relevant ones are,

- The improvements on system understanding by stronger collaboration between multidisciplinary teams and holistic approaches, i.e. system level analysis: Interaction between components, e.g. TES, heat sources, ….
- And the contribution on the obtention of an optimized system design and risk reduction thanks to analysis of different energy concepts (design and control operation) and scenario analysis (e.g. high/low heat demand, changes in energy prices, …).

This document aims to provide basic know-how to help engineers define their modelling and simulation approach for system analysis of large thermal energy storage (LTES) integration concepts, with focus on the early project phase. Notice that the definition of the early phase considered here, opportunity phase, is

[2] QM Holzheizwerke Planungshandbuch (2022). ISBN 978-3-937441-96-2

[3] T. Nussbaumer, S. Thalmann, A. Jenni, und J. Ködel, Planungshandbuch Fernwärme, Version 1.3. Zürich: Verenum Dr. Thomas Nussbaumer, 2018. https://www.verenum.ch/Dokumente/PHB-FW_V1.3.pdf

[4] The system evolves over time through transient changes, i.e. a state (e.g. temperature) changes over time considering their dynamic properties (e.g. thermal mass).

[5] "The formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases" International Council on Systems Engineering (INCOSE) (2007). Systems Engineering Vision 2020. INCOSE-TP-2004-004-02.

based on the definition given within the IEA-ES TCP Task 39 (see Deliverable A4[6] of Subtask A for details). For the sake of completeness, a short description retrieved from the original document is added below.

Opportunity phase: 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.

During the opportunity phase, LTES system modelling and simulation activities focus mostly on conceptual-level analysis. Leaving very specific design questions (e.g. diffuser geometry) out of the scope. Their main role is to facilitate the evaluation of different design and control strategies providing insights on the system performance, e.g.

- Heat flow rates (charged/discharge heat, heat losses, post-heating, …),
- Temperature profile of the LTES,
- Volume flow rate within the system,
- Efficiency of the overall LTES system and their components (e.g. heat pump, solar thermal installation, heat exchangers, …).

The simulation results are a relevant input for the techno-economic and environmental evaluation of the energy concepts as they provide necessary information to calculate most important KPIs of the opportunity phase (see report on KPIs in LTES systems - Relevance of KPIs for different project phases). Thus, the simulation results help to the rough sizing of the main components of one or several energy concepts and to provide a solid basis for the decision-makers on evaluation the potential of LTES integration and identifying the most promising concepts. It is worth mentioning that part of the evaluation can be already included in the model, so that the simulation results already provide the desired KPIs (e.g. EnergyPRO considers OPEX in some modules, but it does not calculate a LCOH. In TRNSYS and Modelica, the calculation of LCOH is usually not built-in the models and needs to be additionally added if desired)

The document discusses different aspects to be considered, see section 2. Additionally, the discussion is enriched by a Q&A section with specific insights on the modelling and simulation approach from the demonstrators' teams within the TREASURE project, see section 3.

[6] IEA-ES TCP Task 39. Deliverable A4: Method to carry out an LTES project, important questions & KPIs - Subtask A main report. 03/04/2024.

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2. Recommendations and considerations on the modelling and simulation approach

The discussion on the definition of a modelling and simulation approach is divided into three sections. The first section “General considerations” addresses the topic with a general view, while the second section “Specific considerations regarding the opportunity phase” takes into consideration the specifics of early project phase (available data, expected outputs, …). The third section graphically summarizes typical aspects that need to be considered when performing simulations of LTES systems.

2.1 General considerations

Some main aspects to be considered and recommendations are:

1. The modelling and simulation of a specific energy concept is in general a time-consuming task, where the exact effort will depend on many factors, among them the complexity of the system being considered and the experience of the modeler. It is important to find a good compromise between added value and effort taken, and to evaluate possible alternatives, e.g. the use of more pragmatic and less resource-intensive approaches. As a good practice, the modelling approach should be addressed in a “sustainable” way, i.e. if possible, define basic and generic models (e.g. templates) that can be used as a starting point for more specific models that will be used through the project (e.g. for different energy concepts or project phases), or even other projects.
2. A model can be understood as a mathematical representation of a real-world system. With help of parameters and equations, the key physical behaviour of the component/system are described. Through experiments (simulations), the model aims to provide answers to specific questions about the system performance. To successfully model a system, it is therefore necessary to have a clear definition of the model purpose and the questions that need to be answered, to have a good understanding of the system, and to combine those aspects to define a useful model with acceptable performance. Notice that:
    - Besides having clarity on the model purpose, it is also important to know specifically how the evaluation of the energy concepts will be done, mainly because the simulation results (together with other datasets) are used to calculate a set of KPIs, and it must be ensured that the required data to calculate those KPIs can be obtained.
    - The simplifications carried out might be forced, e.g., due to a lack of information for model parameters such as exact thermophysical properties of the surrounding soil. However, model simplifications may also be desired, e.g. to keep computational performance high, and include for instance the deliberate disregarding of irrelevant physical phenomena. In most situations, the increase of details being modelled is associated with a decrease of computational performance (reduction of simulation speed) as well as an increase of information required.

Further, mention that when building a simulation model, it is a good practise to provide explanation to each coding line or alternatively an overall explanation for several coding lines which are grouped together. This is both a proactive measure to avoid unnecessary complex coding structure and is very helpful when troubleshooting.

3. Non-technical aspects such as personal preferences (e.g. based on own know-how and experiences), strategic reasons (e.g. library development or ease of finding staff with relevant experience) or practical considerations (e.g. model will be co-developed and/or should be shared within different persons/institutions) may also play a major role in the selection of a simulation environment and partially also in the model selection. Another aspect to consider is the target group of the model, i.e. if this model should be used only for modelers, i.e. specialized personal, or should be provided and used also by a more generalist user group (e.g. planners, project leader, …), within or outside their institution.
4. It is a common approach to model a system in a deterministic way. A deterministic model assumes that all relevant factors are known, allowing future events to be calculated with certainty. However, in reality, the models are only an approximation of a real system, and there is an unknown deviation between simulation results and the real performance. The modeler should be aware of this fact and never communicate the results as an "absolute truth". Since the system under consideration is still in the planning phase and has not yet been built, it is impossible to validate the model by quantitatively comparing its results with measurements from the real (yet non-existent) system. In order to ensure high quality of the results and be able to some extend narrow down their accuracy; it is favourable to prefer models that have been validated and include a reference of the validation work which will give hints on the validity range and accuracy of the models.

   Besides contributions to the inaccuracy from the model itself (e.g. due to disregarded or simplified physic phenomena), inaccuracies can come from a wrong parametrization (e.g. wrong estimation of physical properties) or deviations between the defined and the real boundary conditions. To strengthen the results, a sensitivity analysis of the model parameters is essential to identify the most influential factors that require special attention. Additionally, scenario analysis examining varying boundary conditions such as electricity prices or reduced heat demand can provide valuable insights into the robustness of the energy concept. Both approaches improve the interpretation of the results and yield a better basis for the decision-makers. Finally, if possible, mention that it is also helpful to model and simulate the existing system (Status Quo) to have a complementary reference additionally to the measured data of the Status Quo. This will help to interpret the results and estimate the added value of the energy concepts being evaluated. This is especially interesting in case future scenarios are being considered, e.g. increase/decrease of heating demand, reduction of DH temperatures as there is no measured data from the existing system to compare the results of the proposed energy concepts with.

5. As mentioned in the introduction, the calculation of KPIs e.g. OPEX is already included in some software and models. Breaking the process into distinct steps e.g. 1. simulation studies to obtain main technical outputs (e.g. heat losses, heat production, electrical consumption, etc.), and 2. post-processing to calculate additional KPIs (e.g. LCOH, CO2 emissions, …) is an effective approach. It provides flexibility in the evaluation process, such as adjusting economic boundary conditions for sensitivity analysis, and allows the same routine to be applied to results from different models or even simulation software, provided the necessary data is available in the correct format. A critical consideration is whether information use on the post-processing (e.g. economic boundary conditions such as fuel prices, etc.) do influence the control strategies. If this is the case, a simulation will need to be carried out per each case restricting the use of a separate post-processing.

2.2 Specific considerations regarding the opportunity phase

As mentioned above, the main objective of the opportunity phase is to identify the technical and economic potential for the integration of an LTES. Since this is an early project phase, it is to be expected that the storage integration concept(s) are only partially defined, and many variants can be considered. Based on the information gathered regarding the goal of the LTES (e.g. intermediate storage of waste heat, …), potential sites (e.g. area, …), boundary conditions (e.g. availability of waste heat, temperature levels of supply and return lines, …) different energy concepts can be sketched, modelled, simulated, and evaluated.

In terms of modelling and simulation during the opportunity phase, the following aspects should be considered:

1. The lack of concretization of the energy concept shifts the focus towards the energy concept itself rather than the component selection. Therefore, the use of “generic” models (e.g. heat pump model based on e.g. Carnot quality grade[7]) rather than detailed models that require the definition of a very specific component (i.e. that do require component-specific information such as manufacturer data), are a good compromise between parametrization effort and value of the results.
2. While economic KPIs (e.g. CAPEX and OPEX) are of high and general interest, an exact list of KPIs that are to be used for the evaluation can be hardly generalized and needs to be defined specifically for the cases under consideration.
3. The variety in terms of scenarios (energy concepts, locations, boundary conditions, …) to consider might (project dependent) be large, therefore obtaining an optimal design for every scenario is

[7] (German: Gütegrad): Ratio between the real thermodynamic efficiency and the theoretical ideal efficiency of a reference process (in this case the Carnot process).

neither possible nor the focus of this stage. The focus lays rather on comparing results of different scenarios to discard a location, technology, energy concept, etc., and to have a rough estimation of the added value of the proposed solutions compared between them and to the existing system. A key aspect in this regard is to ensure a fair comparison between concepts by e.g. using a comparable modelling approach (e.g. same assumptions and boundary conditions, similar level of detail on control strategy, …).

4. It is not expected that all energy concepts defined at the beginning as well as the quality of the results are perfect from the very beginning. Therefore, the opportunity phase should be addressed in an iterative way, i.e. simulations are carried out, performance of the different energy concepts for different boundary conditions (temperature, locations, charge-discharge strategies) are obtained, evaluated by means of selected KPIs and discussed, outcomes are used to discard scenarios and potentially new ones are added, the level of detail of the models is adapted as needed and a set of simulations runs is started again.
5. Finally, it should be highlighted that the large number of scenarios being considered yields many simulations results which will be then most-likely post-processed. To be able to interpret (use) the results it is necessary to know where they come from, and thus keep traceability of each simulation result and post-processing step, i.e. document which specific model, parametrization, and boundary conditions, etc. have been used. Furthermore, is interesting to save the models and parametrization set used separately or manage their versions with help of a version control system such as git[8] to ensure not just traceability but reproducibility as well.

2.3 Typical aspects to be considered for LTES system simulation studies

This section graphically summarizes typical aspects that need to be considered when performing simulations of a thermal energy storage within a system. Many of these aspects, as depicted in Figure 1, were adopted from IEA-ES TCP Task 39's subtask C, in which comparative simulations were conducted employing different simulation tools and storage models on pre-defined testcases. The figure was extended by typical aspects that need to be considered when conducting system simulations and should serve as a quick overview without making claims of being complete. For a more in-depth description of the aspects for storage simulation, the reader is referred to the original deliverable of Task 39[9].

[8] Git is a distributed version control system that tracks versions of files. It is often used to control source code by programmers who are developing software collaboratively. https://git-scm.com/

[9] Schmidt, T. et al. Deliverable C2a: Modelling guidelines - Round robin test case description. IEA-ES TCP Task 39. June 2024. Link: https://iea-es.org/task-39/wp-content/uploads/sites/21/IEA-ES_Task39_WPC_Deliverable_C2a_Modelling_guidelines-Round_robin_test_case_description.pdf

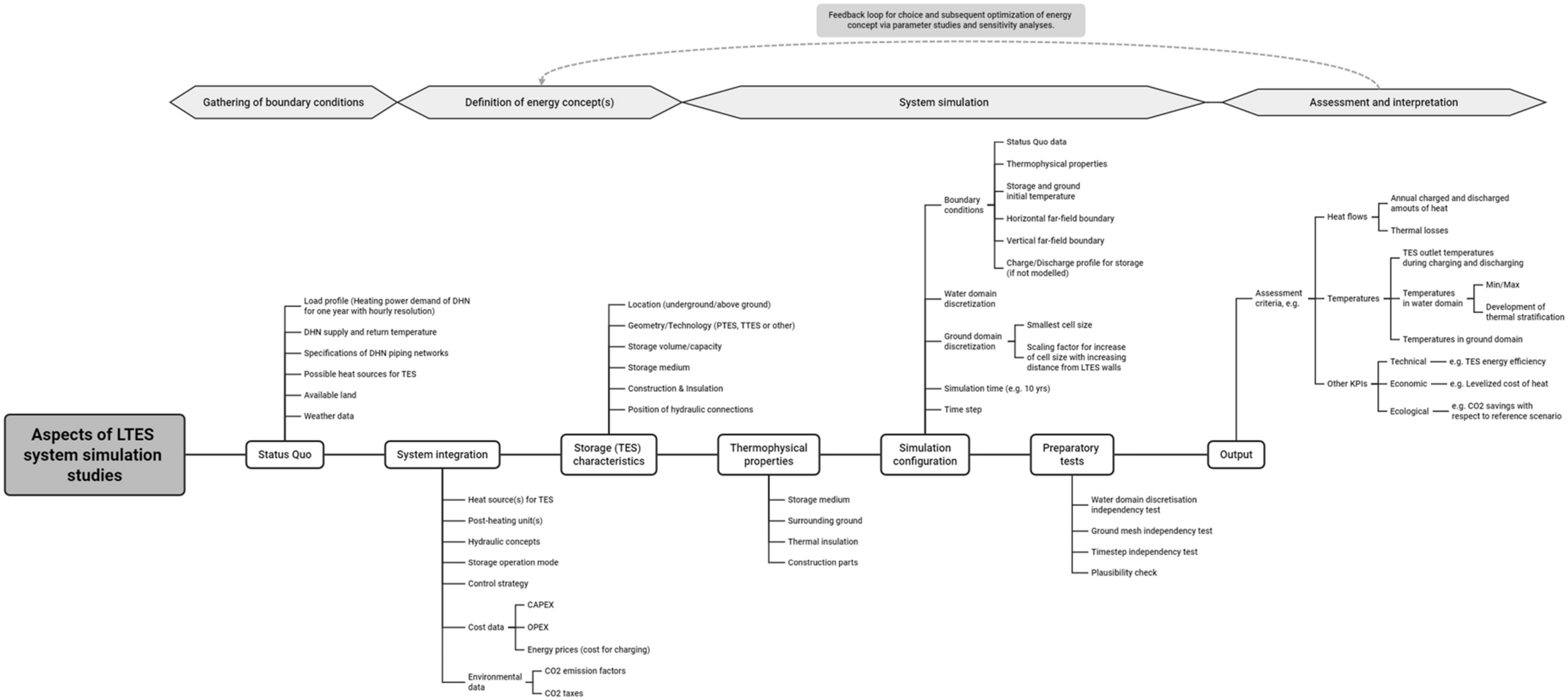

FIGURE 1: OVERVIEW OF TYPICAL ASPECTS TO BE CONSIDERED FOR LTES SYSTEM SIMULATIONS.

3. Demonstrator specific Q&A

In this section, a set of questions that arose during the TREASURE project related to the modelling and simulation approach is listed together with a description on how the demonstrator team has addressed it.

3.1 What are feasible charge and discharge rates for the thermal energy storage?

For the demonstrator in Vienna, the thermal energy storage is meant to be charged and discharged from/to the district heating network. How much and when exactly the charging and discharging of the TES takes place is only partly determined by the TES itself. This decision is rather part of a complex operational optimization task where not only the whole district heating system is considered but also other factors such as the electricity sector needs to be considered (mainly due to a direct coupling of the two sectors caused by the operation of e.g. combined heat and power plants, compression heat pumps and direct power to heat installations). To carry out the operational optimization and be able to derive a charge-discharge plan for the TES, a mathematical description of the TES is added to a large model used for an operational optimization specialized tool. Among the information to be set there is the definition of a charge and discharge rate. Though the charge and discharge rate are to some extend part of the design process, some first reasonable estimations are needed to be able to start the analysis on how a specific TES would be best integrated into the existing system. Hence, the question arises, what are reasonable assumptions on the charge and discharge rates for the specific large thermal energy storage?

There are several factors that influence the charge/discharge capacity of a TES, among them the maximal feasible flowrates, system temperatures and heat exchanger effectiveness. These factors do depend on other aspects at design level such as heat exchanger size and configuration, pipe diameters, pump characteristics as well as on factors at operational level e.g. storage temperatures, ramp-up speed of the pumps. Some of the mentioned factors cannot be directly controlled (e.g. TES temperatures) while others related to the LTES system design are. In summary one can say that the determination of a single and maximal charge/discharge capacity is not straightforward and that the analysis of all the different factors would be a time-consuming task.

A reasonable approach for the early project phases, is to make use of already available experience, e.g. from existing similar TES projects. A list of LTES projects has been collected (see Table 1 in the section Annex A: Overview of existing LTES projects). It includes information on e.g. dimensions (height, volume, …), nominal operating conditions (min/max temperatures, and nominal discharge and charge flow rates). Under consideration that the values listed in the table do represent a reasonable operation, these values can be used to derive reasonable discharge and charge rates for a similar LTES, e.g. the LTES under consideration. It is worth mentioning that some of the storages listed in Table 1, specifically 7 to 11, were part of the SPICE[10] project (FKZ: 03ET1322A). In this project several aboveground tank thermal energy storages (TTES) in the range of 2.000 to 43.000 m^3 located in CHP-based district heating systems were analyzed with fiber optic temperature sensing. The results were not only described in detail in the final report, but also with the help of short videos for different charge-discharge patterns, providing additional valuable information in regards of the temperature profile during real operation.

Though the range of volume flow rates might vary significantly from one project to another, see Table 1 in the section, the review of the existing projects helps to ensure that the first assumptions taken are reasonable and can be used as a starting point in early project phases. For the 40.000 m^3 TES under planning in Vienna, the existing TES #7 to #13 of the Table 1 are the most similar in terms of size and geometry/technology from which experiences and design parameters can be derived. Looking at their characteristics in regards of charge and discharge capacities in MW_{th} and m^3/h, we observe two subgroups, see Figure 2 and Figure 3. TES below 25.000 m^3 that operate at charge/discharge capacities below 34 MW_{th} and 900 m^3/h, while larger TES, 30.000 m^3 or higher, which have much larger charge and discharge capacities. Also notice that in some cases the discharge (negative values) and charge capacities are not symmetric, e.g. Storage 3 of the SPICE project can discharge up to a rate of 269,3 MW_{th} but has a maximal charging rate of “only” 43,4 MW_{th}.

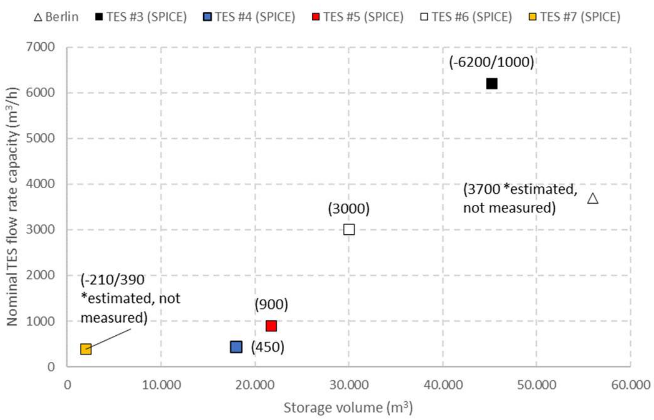

FIGURE 2: NOMINAL (MAXIMAL) VALUE BETWEEN DISCHARGE (NEGATIVE VALUES) AND CHARGE FLOW RATE CAPACITY IN m^3/h AS A FUNCTION OF STORAGE VOLUME. A SINGLE VALUE AT THE LABEL IS SHOWN FOR TES WITH SYMMETRIC FLOW RATE CAPACITIES FOR THE CHARGE AND DISCHARGE PHASE.

[10] Andreas Herwig, Luise Umbreit, and Karin Rühling. “Temperaturfeldmessung in Großwärmespeichern von KWK-Basierten Fernwärmesystemen Als Werkzeug Zur Effiziensteigerung: Projekt SPICE (Speichereffizienz).” Technische Universität Dresden, August 8, 2019. https://tu-dresden.de/ing/maschinenwesen/iet/gewv/forschung/forschungsprojekte/spice.

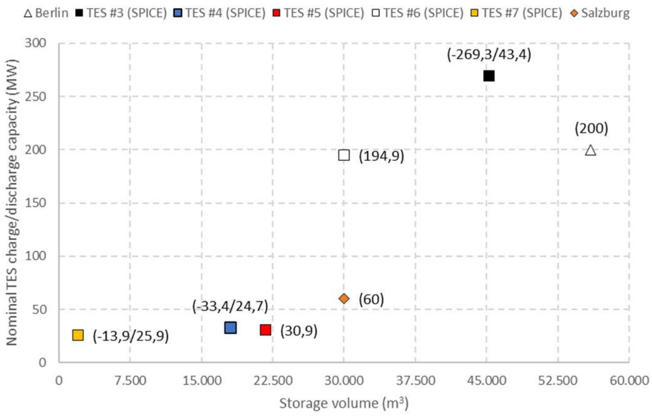

FIGURE 3: NOMINAL (MAXIMAL) VALUE BETWEEN DISCHARGE (NEGATIVE VALUES) AND CHARGE CAPACITY IN MW AS A FUNCTION OF STORAGE VOLUME. A SINGLE VALUE AT THE LABEL IS SHOWN FOR TES WITH SYMMETRIC CAPACITIES.

Based on the values from the existing projects, especially #3 and #6 of the SPICE Project and the storage in Berlin, we could say that for the TES in Vienna, large capacities of up to 200 MW (3000 m^3/h) can be achieved (assuming a proper design and that no other restrictions limit such capacities). Values in the range of 20 to 30 MW_{th} (200 to 900 m^3/h) are definitively achievable as most large TES (>2.000 m^3) can handle such capacities. Finally, it should be mentioned that,

- The height over diameter ratio of the Vienna would be about 0,73 and thus similar but slightly smaller than the value for the three large TES mentioned which are in the range of 0,9 (TES #3) to 1,33 (TES #6).
- Charge/discharge capacities obtained are within the range of values proposed by the IEA-ES Task 39 experts. Range can be observed in the diagram provided in their Task 39 Introduction document[11], see Figure 4. Notice that values for other TES technologies (PTES, BTES and ATES) are also provided.

[11] IEA-ES Task 39 brochure Large Thermal Energy Storages for District Heating. Introduction. 22/02/2024. Linnk: https://iea-es.org/task-39/wp-content/uploads/sites/21/IEA-ES_Task39_WPA_Deliverable_A0a_Task_brochure%E2%80%93Introduction.pdf

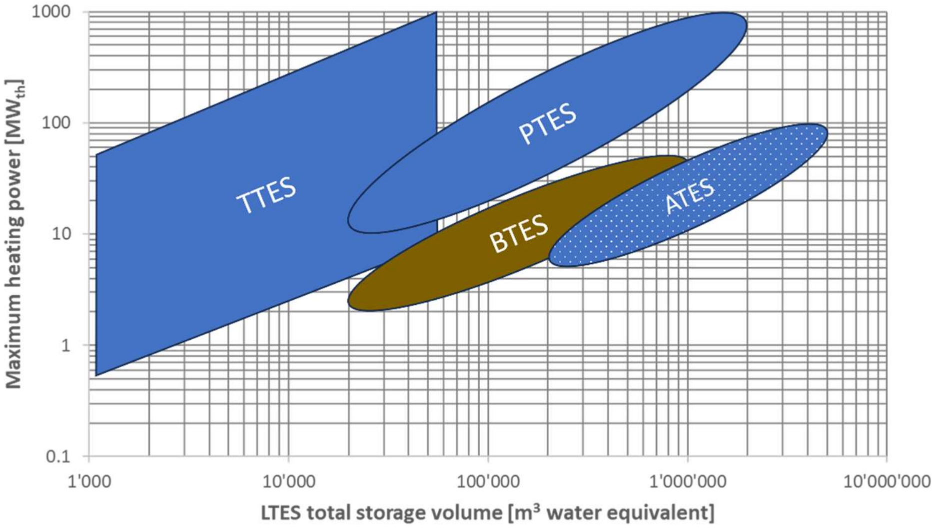

FIGURE 4: TYPICAL CHARGE/DISCHARGE CAPACITY RANGE IN MW AS A FUNCTION OF STORAGE VOLUME FOR DIFFERENT TYPES OF LTES: TTES, PTES, BTES AND ATES. SOURCE: IEA-ES TASK 39[11].

The literature research on existing project should be sufficient to set a first assumption. A more detailed analysis on this topic is not usually done in the opportunity phase, the main reason is that the questions addressed in the opportunity phase (comparison of energy concepts, rough sizing, …) do not require a high level of detail in this topic (unless this is critical for the energy concept). In any case, demonstrators that do desire a more detailed analysis on the maximal charge/discharge capacity are encouraged to follow up on the topic of mixing in LTES as this might be one of the relevant aspects to consider on defining a constraint for the maximum charge/discharge volume flow rates, and thus capacity. A short list of CFD simulation studies related to this topic are provided in the section "Annex B: List of simulation studies on TES mixing".

3.2 Which TRNSYS type to use for the modelling of PTES?

A good starting point is to review the overview of TRNSYS models for PTES, TTES, ATES and BTES provided by Deliverable C1[12] of IEA-ES TCP Task 39. This document also provides a list of relevant models for other simulation environments e.g. MATLAB, Modelica, etc.

The PTES listed in the publication are,

- Type 343 (cone)

[12] Schmidt, T. et al. Deliverable C1: Numerical models list – Overview and collection of model fact sheets. IEA-ES TCP Task 39. June 2024.

- Type 1322 (pyramid)
- Type 1535/1301 (cone)
- UGSTS

Notice that Type 1322 and UGSTS are not available to the public.

And the TTES (cylinder) are,

- Type 340 (above ground)
- Type 342 (buried and above-ground)
- Type 534/708 (ground buried)
- Type 1534 (above ground)
- Types 1534/1302 (ground buried)

The deliverable C1 document includes fact sheets for all models listed providing some general but relevant information such as model author, availability (e.g. open source) and relevant publications. Additionally, information on the modelling approach highlighting features and limitations is also briefly presented.

As we know, the model to be used will depend on different factors, one of them and very important is the aim of the modelling work. In this regard, is worth to mention the model comparison work between TRNSYS models reported in HEATSTORE-TR2.3[13]. The report compares the accuracy and performance of three models, Type 342, Type 1322 and the Types 1300/1301[14]. It was concluded that all models give accurate results with regards to heat balance and temperature distribution. Therefore, the authors suggest utilizing the fastest model (Type 342) for pre-feasibility studies and keep the use of more accurate models such as Type 1300/1301 for more detailed feasibility studies. Type 1322 (which has a 3D representation of the PTES) can be used for more detailed feasibility studies, but is much slower than Type 1300-1301. In case the soil and weather conditions of the PTES location are well known, the use of the detailed models (e.g. Type 1322) can be justified, since the results obtained with design parameters (without parameter calibration) of the detailed models is much accurate than the simple (but fast) Type 342.

[13] Gauthier, G. (2020): Benchmarking, and improving models of subsurface heat storage dynamics. Comparison of Danish PTES and BTES installation measurements with their corresponding TRNSYS models. GEOTHERMICA – ERA NET Cofund Geothermal. 47 pp.

[14] This TRNSYS type is now replaced by the combination of Types 1535/1301 in the newest version of the TESS libraries (from end 2021 and onwards)

Annex A: Overview of existing LTES projects

TABLE 1: OVERVIEW OF LTES AS BASIS FOR ASSUMPTION OF REASONABLE CHARGE AND DISCHARGE RATES.

#	Location, storage type	Storagevolume (m³)	Storage diameter (m)	Storage height (m)	Storage heigh to Diameter (m/m)	Discharge/charge power (MW) (i)	Volumetric flow rate Discharge/charge (m³/h) (i)	Cycle frequency per year (-)	Temperature range (°C), ΔT	Charging unit materials	Diffuser / Piping	Source	Remarks
1	Dronninglund, DK, underground pit	60000	71,4 (calculated)	15	0.210	27	306.8	1 - 2	12 - 89, (77)	Satianless steel	3 Radial diffusers / Bottom piping	[1], [2]	During the operation period from 2014 no major problems have turned up. Water ponds are regularly removed from the lid and water can occur in the insulation maybe becausewater from water puddles on the lid comes through the ventilation valves. A yearly diver inspection shows no corrosion signs and clear water.
2	Marstal, DK, underground pit	75000	77,3 (calculated)	16	0.207	10	123.2	1 - 2	17 - 88, (71)	Black steel	3 Radial diffusers / Wall piping	[2]	The overall experience in the operation period from 2012 until 2017 is that the storage functions well, but some minor problems have turned up:After one year corrosion was found by a diver inspection of the storage. The problem was that galvanized metal was mixed with iron and that organic material in the water gave possibilities for bacterial corrosion. PH has now been changed from 7.4 to 9.8 and galvanized metal replaced. The heat exchanger between storage and energy system was very ineffective. The reason was sludge from the storage water. The heat exchanger was cleaned and a filter had to be implemented in the heat exchanger inlet. Two holes in the liner have been located in the yearly diver inspection. The holes have been patched by a diver.
3	Ulm, GER, above ground tank	2500		-		28	408.3	365	70 - 130, (60)	-	-	[1]	Pressurized single tank
4	Potsdam, GER, above ground tank	41000		-		20	624.9	-	70 -98, (28)	-	-	[1]	
5	München, GER,	5700	21,3 (calculated)	16	0.751	2	23.3	1-2	15 - 90, (75)	Stainless	Stratifier	[1], [4]	
6	Hannover, GER, above ground tank	2750										[6]	In operation since June 2000. A new high-density concrete material was used to built this storage for the first time. This material has such a low vapour permeability that an additional liner can be omitted. Another development was achieved by fixing an additional charging and discharging device with a variable height in the middle of the storage volume. With this device, the temperature stratification in the store can be improved and simultaneous charging and discharging becomes possible.
7	GER, above ground tank	45240	40	36	0.900	-269,3/43,4	-6 200/1 000	-	60 - 98, (38)	Black steel	2 Radial diffusers	[3]	Speicher 3 of SPICE Project.
8	GER, above ground tank	18000 (10000/8000)	20	60 (35/25)	3.000	24,7 (-33,4)	450	-	Top: 50 – 98, (48). Bottom: 60 – 125, (65)	Black steel	4 Radial diffusers, Wall piping	[3]	Speicher 4 of SPICE Project. 2-Zonenspeicher
9	GER, above ground tank	21730	26.3	42.8	1.627	30.9	900	-	68,6 – 98,1, (29)	Black steel	2 Radial diffusers, Wall piping	[3]	Speicher 5 of SPICE Project.
10	GER, above ground tank	42000 (12000/30000)	30	57 (17/40)	1.333	194.9	3000	-	60 - 115, (55)	Black steel	2 Radial diffusers, Wall piping	[3]	Speicher 6 of SPICE Project. 2-Zonenspeicher. Nur die untere 40 Meter (30000 m^3) werden als Wärmespeicher verwendet.
11	GER, above ground tank	2000	15.2	12	0.789	-13,9/25,9	-210…390 (estimated, not measured)	-	40 - 98, (58)	Black steel	2 Radial diffusers	[3]	Speicher 7 of SPICE Project.
12	Berlin, GER, above ground tank	56000	43	45	1.047	200			55-98 (43)			[7]	The thermal storage facility is located on the power plant site right next to Europe's largest power-to-heat plant, which converts surplus wind or solar energy into heat on site.
13	Salzburg, AUT, above ground tank	30000	29.46	44	1.493	60						[8]	Commisioned in 2011
14	Linz, AUT, above ground tank	34500	26.00	65	2.500				97-60		2 Radial diffusers	[9]	Commisioned in 2004

List of references for Table 1,

[1]. IEA ECES - Applications of Thermal Energy Storage in the Energy Transition – Benchmarks and Developments, 2018.
[2]. Sorensen et al., Design and Construction of Large Scale Heat Storages for District Heating in Denmark, 2018.
[3]. Andreas Herwig et al., Temperaturfeldmessung in Grosswärmespeichern von KWK-basierten Fernwärmesystemen als Werkzeug zur Effizienzsteigerung, 2019.
[4]. Solites, Technisch-wirtschaftliche Analyse und Weiterentwicklung der solaren Langzeit-Speicherung, 2012.
[5]. PlanEnergi et al., IEA DHC Pit Thermal Energy Storage for Smart District Heating and Cooling - Technical report on model validation, cost functions and results of an exemplary base case study, 2020.
[6]. Schmidt, T. et al. Central solar heating plants with seasonal storage in Germany, Solar Energy 2004.
[7]. Wille, Joachim (2022, July 3). Deutschlands größter Wärmespeicher. Klimareporter. https://www.klimareporter.de/technik/deutschlands-groesster-waermespeicher.
[8]. Salzburg AG. STROM UND WÄRME DURCH KRAFT-WÄRME-KOPPLUNG.
[9]. Pauli, H. (2024, March 19). Erfahrungen aus dem Betrieb eines Fernwärmespeichers IEA ES Task 41.

Annex B: List of simulation studies on TES mixing

Specific literature on detailed analysis of PTES is available in the literature, e.g.

- Recent research[15] uses a three-dimensional model to analyse the dynamic behaviour of inlet mixing inside the PTES. The model is validated against measurements of the Dronninglund PTES.

- Research by Fan, J. et al.[16] investigates experimentally and numerically the thermal behaviour of a 75000 m^3 water pit heat storage in Marstal solar heating plant. Thermal stratification in the water pit heat storage and its interaction with the ground are elucidated by calculations using the validated CFD model.

Otherwise, literature from similar TES technologies might also be helpful, e.g.

[15] Xiang, Y. et al. (2023) Assessment of inlet mixing during charge and discharge of a large-scale water pit heat storage, Renewable Energy, 2023, ISSN 0960-1481, https://doi.org/10.1016/j.renene.2023.119170.
[16] Fan, J. et al. (2017) Experimental and theoretic investigations of thermal behavior of a seasonal water pit heat storage. Paper presented at Solar World Congress 2017, Abu Dhabi, United Arab Emirates. DOI:10.18086/SWC.2017.13.03

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- The main objective of the doctoral thesis by Rodríguez Pérez, I.[17], is the numerical resolution of heat transfer and fluid flow problems in cylindrical coordinates and its application to the study of the unsteady simulation of the convection phenomena in storage devices for solar thermal systems in the low-to-medium temperature range (20 to 60 °C). Especially relevant for the reader are chapter four and five, which deals with the transient phenomena in TES.
  Chapter four do focus on thermal stratification and its degradation due to the inlet mass flow rate. Both charging and discharging phase are investigated. For the unloading case a 300-liter horizontal tank with length 1,5 m and internal diameter 0,5 m is considered. Initial temperature is constant at 42 °C and inlet cold water at 20 °C is injected. Different volume flow rates are analysed (60 to 360 l/s). For the loading phase a 373-liter vertical cylindrical TES with a height to diameter radius of 2,5 insulated with 44 mm thick fiberglass material is investigated. Different tests (different initial and inlet temperatures) are carried out.
  Chapter five on the transient natural convection during the cooling phase. Here different tank volumes (0,1 to 0,4 m^3), height to diameter ratios (1 to 3,45) and insulation thickness (0 to 0,04 m) have been investigated.

[17] Rodríguez Pérez, I. (2006) Unsteady laminar convection in cylindrical domains: numerical studies and application to solar water storage tanks. Doctoral thesis. Universitat Politècnica de Catalunya. 2006. ISBN: 9788469064931.