# ADVANCES IN MODELING AND EVALUATION OF LARGE-SCALE HOT WATER TANKS AND PITS IN RENEWABLE-BASED DISTRICT HEATING

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## Abstract

Large-scale seasonal thermal energy storage (TES) emerges as a promising component in the future renewable-based district heating (R-DH) systems whereby large shares of renewables are being integrated. To enable such storage systems with large volumes to fulfill the seasonal tasks with high technical efficiency at cost-optimal level, they should be thoroughly examined, properly designed and planned. Thus, simulation-driven assessments are crucial to investigate these systems in order to avoid high capital cost with performance below expectations. While detailed finite-element simulations inspect multi-physical aspects (e.g. conduction, convection, mass transfer), dynamic simulation and pre-design tools are inevitably needed to capture the system's energy flows. Consequently, this work reports and reviews the development of a wide variety of numerical models and their validation for advanced TES applications.

*Keywords: Hot water tank, buried pit, numerical modeling and simulation, renewable-based district heating, seasonal thermal energy storage, co-simulation approaches.*

## 1. Introduction

To properly phase-out the conventional fuels (e.g. natural gas) and pave the way toward the decarbonization of the heating sector, alternative substitutes have to be accordingly addressed. Thus, the integration of alternative energy resources (e.g. solar energy, geothermal, industrial waste heat) found its place favorably in district heating (DH) systems whereby the share of renewables is gradually increasing forming the so-called renewables-based district heating (R-DH) systems (Ochs et al., 2019). Yet, it is important to mention that the renewables are often subject to a major pitfall as they seasonally and daily fluctuate leading to the intermittency by which heat might be available when it is not required. Thus, the integration of renewables might alter the overall national energy scheme (Dahash et al., 2019a) and some risks might appear (e.g. security of supply is violated). Hence, large-scale seasonal thermal energy storage (STES) plays a key role in R-DH systems as it is capable to bridge the gap between the renewables' availability and heat demand eliminating the mismatch (Dahash et al., 2019a).

Accordingly, it is held that a large-scale and long-term TES enables a more flexible integration of renewables in DH systems and, as a result, has benefits in terms of lower fossil fuels consumption, higher primary energy savings and lower $CO_2$ emissions. Yet, the high capital cost associated to STES is frequently seen as a major downside. Together with the space availability, complex planning layout and the presence of groundwater tables, these are the set of major challenges in STES domain to be tackled among others (Dahash et al., 2019a). Thus, simulation-based analyses are perfectly suited to the planning phase of such large-scale systems since its construction is considered a complex process.

## 2. Challenges in Planning and Construction of Seasonal TES

To select properly the design, geometry and construction type for a large-scale seasonal TES, a great number of inputs (hydro- geological factors, system characteristics, thermal losses, investment cost, etc.) have to be repetitively evaluated until a compromise between the technical performance and the economic feasible investment is found (Dahash et al., 2019a).

Fig. 1 schematically demonstrates the role of the most significant parameters influencing the construction of buried TES. Therein, the different players are classified into different categories and accordingly assigned

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following their impact on the desired type of the storage. Firstly, the site's ground conditions (e.g. soil excavation) have a direct impact on the capital cost, whereas the indirect impact is seen as it influences the construction type. The site has a further impact on the TES geometry (maximum available surface, maximum depth, etc.) when considering the static loads (e.g. pressure forces) implied on TES. Next, the application (e.g. heat-supply system) into which the TES is being integrated is strongly influenced by the storage duration (buffer or long-term TES) through the number of charging cycles from an operational point of view. This influence has in return an impact on the construction type of the TES, which subsequently influences the capital costs and, therefore, the cycle number has also an impact on the capital costs. Thereby, it is difficult to determine the optimum type of TES and its corresponding construction without the aid of numerical simulations and profound reliable key performance indicators (Ochs et al., 2015a).

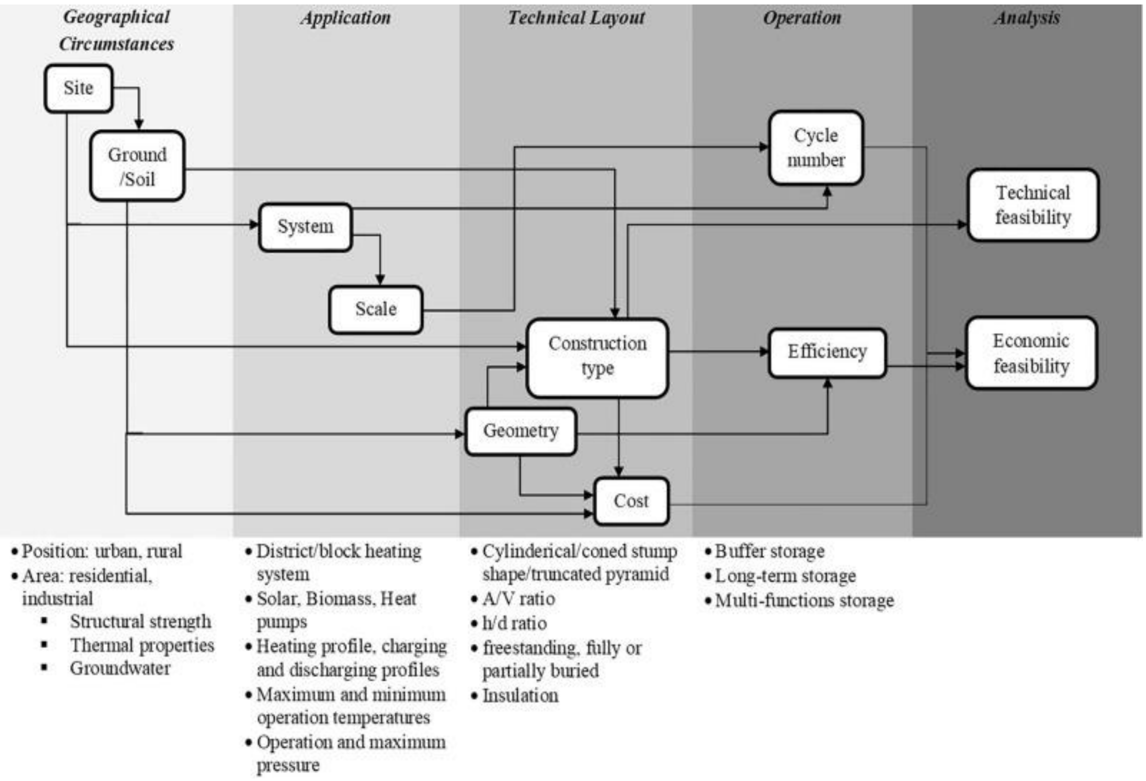

**Fig. 1: Schematic representation of the most influencing parameters on the construction of large-scale underground TES and its economic feasibility (reproduced from (Dahash et al., 2019a)).**

Further, the construction type has an impact on the heat-supply system efficiency as well on the TES. For instance, Ochs et al. (2019) compared the efficiency of two TES geometries (i.e. conical pit and cylindrical tank) under the same set of boundary conditions concluding that the tank outperforms the other option. Then, the efficiency affects the economic feasibility and, subsequently, the TES geometry disturbs the economic feasibility as the tank is often seen the most-costly option for STES. Thus, in the framework of an international project entitled "Giga-Scale Thermal Energy Storage for Renewable Districts" (giga_TES, 2019), an ultimate milestone is to set the planning guidelines and tools for different TES construction types (i.e. tanks, conical pits, pyramid pit) under different boundary conditions (e.g. groundwater existence/flow). It is held that such guidelines will help the engineers and researchers later to understand better which construction type is perfectly suited to the given tasks and can withstand the different challenges. Thus, the project also investigates a number of simulation tools for the modeling of large-scale seasonal TES with different operation parameters and boundary conditions.

## 3. Modeling and Simulation of Large-Scale Seasonal TES

The interconnections between the different categories shown in Fig. 1 highlight the importance of TES simulations. Besides, the construction of large-scale TES systems tends to be costly and, therefore, this inevitably demonstrates the significance of TES modeling to guarantee the economic feasibility and the effective planning layout for the system. As a result, modeling process suits ideally to these tasks and helps in understanding the operation of these systems, which permits in producing the optimal planning and later developing them. Consequently, it is remarkable that TES modeling simulations can be categorized into a wide range of levels following the goal of the investigation. Hence, TES modeling undergoes a systematic process in which the goals are pre-design, detailed design, technology integration, evaluation and optimization.

Fig. 2 reveals the TES modeling process hierarchy whereby at the early phase of TES construction a pre-design tool is frequently used for the planning phase and, then, details are consecutively included in the model until it reaches a detailed model. Next, the TES undergoes a technology investigation as it is integrated within an energy system (e.g. DH system). Accordingly, the TES technology is thoroughly evaluated and the outputs are post-processed resulting into some optimization proposals (e.g. material development, optimal construction type, optimum insulation thickness and DH operation control strategies). Meanwhile, it is important to keep in mind that there exist three factors strongly influencing the computation time: level of detail (pre-design, detailed), number of components (technology integration) and simulated time (daily, multi annual). These players might dramatically alter the computation time as shown in Fig. 3. In order to optimally select the right level, the aim of analysis should be beforehand defined.

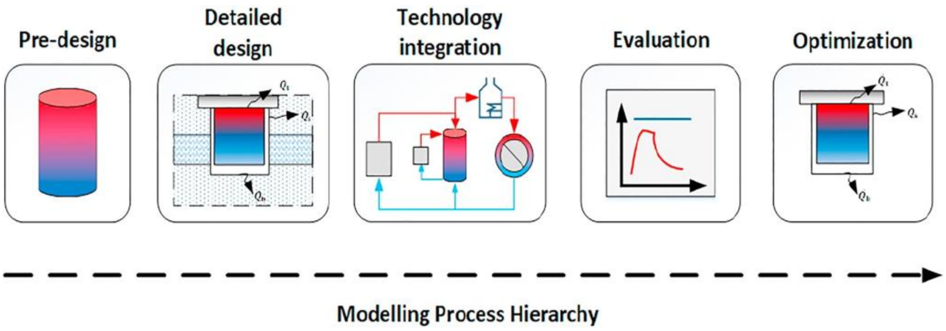

**Fig. 2: An exemplary hierarchy for modeling process of large-scale TES in DH systems (reproduced from (Dahash et al., 2019a)).**

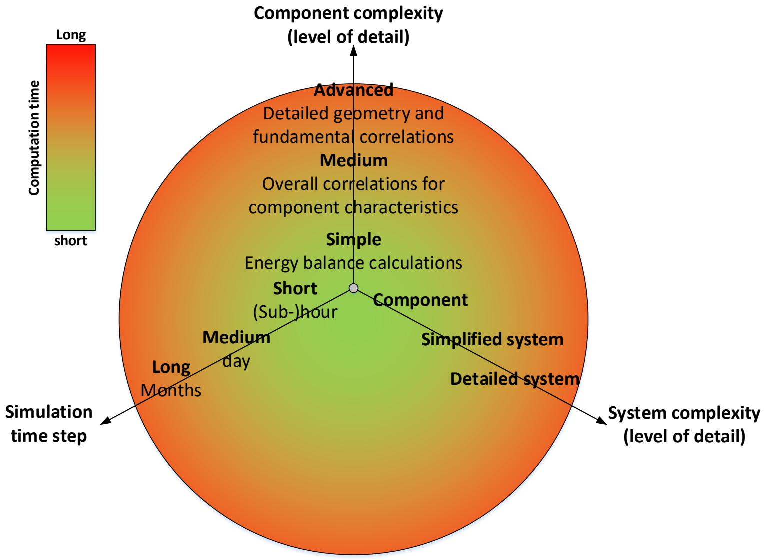

**Fig. 3: Computation time for TES simulations.**

For the pre-design level, some prototyping tools are used to give a glimpse on the TES and its integration and these tools produce preliminary performance indicators. Out of these tools, an online solar district heating (SDH) tool can be used for the preliminary cost-benefit analysis (Solites, 2013). This tool supports both centralized and decentralized SDH systems. Within “*giga_TES*” project, a pre-design tool is developed using Microsoft Excel and is known as “Load Profile Generator” (O’Donovan, 2019). It is as a simple monthly-balance tool that simulates TES with a 3-nodes model neglecting thermal losses to the environment.

Given the complexity seen when modeling the thermo-hydraulic behavior (stratification, buoyancy, etc.) of large-scale TES systems, a wide range of tools is usually used in modeling TES systems. Such tools are commonly categorized into three types: (a) energy system simulation (ESS) that involves tools like Modelica/Dymola, TRNSYS, Matlab/Simulink, (b) building physics envelope heat and mass transfer tools such as WUFI Pro and Delphin, and (c) computational fluid dynamics (CFD) such as ANSYS Fluent, OpenFOAM and COMSOL Multiphysics (which is also used for building envelope heat and mass transfer).

Accordingly, it is crucial to point out that different discretization schemes are used in simulation tools. Herein, the discretization of the spatial domain is executed using either finite element method (FEM), finite difference method (FDM) or finite volume method (FVM). Besides, the level of detail profoundly depends on the model's dimensionality. For instance, highly-detailed models require 3-D representation and as the level of detail becomes less required, then the model can be reduced to 1-D model.

ESS tools (e.g. Modelica/Dymola) often employ FDM as discretization fashion for models represented as 0-D or 1-D. Yet, it is possible to develop 2-D models in such tools but the computation time might exceed the limits. On the other hand, CFD tools (e.g. ANSYS Fluent) require exact representation for the investigated case and, thus, 2-D or 3-D representation become more important. In order to carry out accurate CFD predications, CFD models are often discretized in FVM or FEM fashion. Further, heat transfer problems call the necessity for accurate domain representation and the utilization of FEM. For example, the TES surrounding soil can be developed in COMSOL Multiphysics as an axisymmetric 2-D model that is discretized in a FEM fashion. Accordingly, this section reports the most common techniques used in modeling TES based on the component level (detailed), TES level, system level and the coupling of all.

### 3.1 Component-level modeling

Herein, it is strongly significant to emphasize the term "component-level" modeling. This arises from the fact that, for example, the domains (cover, liner, insulation, groundwater and surrounding soil) shown in Fig. 4 can be all together realized in one single model forming a stand-alone component-level model that represents the TES envelope domain with its insulation, charging/discharging devices and surroundings domains. Otherwise, the term also encompasses that each single domain (e.g. insulation) can be developed individually in one component-level model, which is later coupled to another component-level model (e.g. fluid domain) and, therefore, the result is a compact model that encompasses two or more component-level models. Whereas the term system-level modeling (the following subsection) stands for the process in which TES is treated as an energy system integrated into a larger energy system and, thus, system-level is widely custom for the overall energy system.

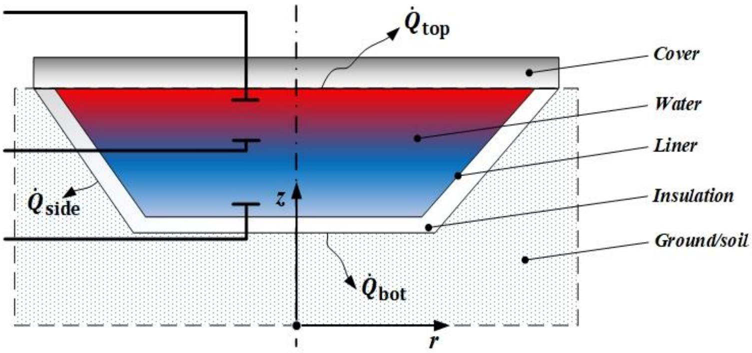

**Fig. 4: An exemplary 2-D representation of an underground shallow pit with the different domains (Dahash et al., 2020a).**

In component-level category, the TES is systematically modeled; subsequently, producing a detailed model. Accordingly, a numerical modeling approach has been broadly employed for component level modeling because it enables the inclusion of a comprehensive range of physics, sketches the desired geometry of the TES component and allows the integration of the surroundings' heat transfer (mainly the one between the soil and the TES). Therefore, CFD is used in which the models are exact representations of the actual component geometry in a discretized fashion. Besides, all transport mechanisms (e.g. moisture transfer in TES envelope) occurring in reality can be considered in CFD models.

Numerical modeling of hot water tanks has been extensively paid a great attention in the literature. Nevertheless, there were little efforts made for modeling large-scale hot water tanks numerically, especially in the case of underground tanks. For instance, Panthalookaran et al. (2008) developed numerical computational fluid dynamic (CFD) models ideally suited for specific tasks (i.e. charging/discharging modes). The models were calibrated against measured data from two buried TES tanks in Germany. One of the tanks is installed in Hannover–Kronsberg with a volume of 2750 m$^3$, whilst the other is the underground TES in Friedrichshafen–Wiggenhausen with a volume of appx. 12,000 m$^3$. The models were used to develop a new characterization method for performance evaluation of various boundary designs during standby mode in large-scale stratified TES (Panthalookaran et al., 2011). Other than those, it is challenging to find other published CFD models that are valid for large-scale underground storage tanks.

On the other hand, the numerical modeling of large-scale pit TES has been lately investigated in the literature. For instance, Chang et al. (2017a) presents a CFD model for a PTES component with transient conditions. Therein, the transient natural convection in a PTES is examined and, subsequently, the mechanism of temperature stratification driven by buoyancy phenomenon is reported. Additionally, the model was validated with experimental data from in-situ test rig with a lab-scale. Later, the model was used to evaluate the thermal performance of a PTES for different key characteristic parameters (Chang et al., 2017b). Therein, it was observed a degradation in stratification degree, which was strongly attributed to the decrease in the PTES depth and, thus, less thermal efficiency. Another conclusion was that PTES thermal efficiency drastically decreases as the slope angle becomes smaller (Chang et al., 2017a). It can be concluded that as the depth decreases with a decrease in slope angle, the upper and lower perimeters of storage increase resulting in unfavorable values of aspect ratio (H/d). Furthermore, Fan et al. (2017) investigated numerically and experimentally the thermal behavior of the seasonal water pit heat storage (a total volume of 75,000 m$^3$) in Marstal solar heating plant (Denmark) by means of a CFD model for short simulation periods. In this model, the interaction between the heat storage and the ground itself is also included.

Moreover, Urbaneck (2004) investigated the thermal behavior for a gravel-water pit TES in Chemnitz, Germany by means of CFD simulations for short simulation periods. Therein, the pit model was validated and, then, a parametric study was performed to determine the effective thermal conductivity of gravel-water medium. Also, the effects seen during charging/discharging modes were examined and explained by means of this CFD simulation. It is observed that large-scale and flat vortices occurred during water exchange (charging/discharging) and they existed for several hours after the exchange process.

Despite the detailed outcomes revealed by CFD models, CFD simulations inevitably call a necessity for large computation efforts as their simulations demand the solution for a set of partial differential equations (PDE) to provide the corresponding physical values (e.g. temperature, pressure, humidity, velocity etc.) and, Accordingly, great computation efforts are required for large-scale seasonal TES for (multi-) annual system simulations, which is currently not feasible and probably not in the near future (Ochs et al., 2009a). Hence, CFD simulations were perfectly tailored for investigations during TES standby mode or short-term operation. Furthermore, another drawback of CFD models is that any slight change in geometry is related with a complex numerical mesh generation. Consequently, assumptions are frequently set for a number of inputs (e.g. material properties and boundary conditions) in simulation studies. These assumptions produce, in fact, a positive notable reduction in the computation efforts forming the so-called “coarse models” (Ochs, 2009b).

Coarse models simplify the geometry investigated and, subsequently, do not depict the exact thermal hydraulic behavior resulting into inaccurate account for the thermal losses (Ochs, 2009b). Regardless of these shortcomings, there have been quite extensive work to develop dynamic models for large-scale underground TES systems in different simulation environments. For instance, several coarse models are applicable for large-scale TES systems in TRNSYS simulation environments (Schmidt et al., 2018a). Those coarse models, however, consider one-dimensional flow inside TES (FDM or plug flow). One of these coarse models is the XST-model (type 342) that simulates buried cylindrical water tanks (Raab et al. 2005). Another model is the so-called ICEPIT-model (type 343), which represents buried gravel-water pit TES (Hornberger, 1998). It is worthy to mention that ICEPIT-model outperforms XST-model because it permits simulating several shapes (i.e. cylindrical geometries and truncated cones), whilst the XST-model simulates only cylindrical geometries (Ochs, 2015b). In addition, ICEPIT-model is able to use water as storage medium instead of gravel-water, which makes this model more advantageous than XST model. Moreover, there exist other tank models (e.g. type 534, type 4) in TRNSYS environment. Yet, it is often argued whether type 534 and type 4 are perfectly capable to represent large-scale STES. On a brighter note, Li et al. (2019) examined the influence of 3 control strategies on the overall performance of an S-DH system equipped with a 3000 m$^3$ pit TES using the model type 534 to represent PTES. Compared to types 342 and 343, TES model type 534 demands an individual ground model when TES is buried.

Ochs (2009b) compared both models (i.e. type 342, type 343) using experimental data for large-scale underground TES and, subsequently, he concluded that both models provide comparable results but they are not sufficiently flexible with respect to geometry and, subsequently, they may not accurately depict the heat and moisture transfer. This is because both models employ FD method for modeling the heat conduction in the ground, whereas it is important to use FEM for complex geometries.

Furthermore, the engineering consulting company (*Thermal Energy System Specialists (TESS)*) established a 3-D model for STES simulations with different cross-sections based on a special request from the Danish STES planning company (PlanEnergi), which owns the copyrights of this model. It is noteworthy to mention that this model is a segmental 3-D model in which only a quarter of the STES is computed, whilst symmetry planes are assigned for the remaining STES domain in order to reduce the computation efforts. In this context, Klöck (2018) carried out the calibration of this model with different cross-sections (e.g. circular or rectangular) against measured data from Dronninglund pit storage (Schmidt and Sørensen, 2018b).

Hence, it is essential to develop dynamic models (FD models) for underground tank TES that can be effectively coupled to other models (FE models) that examine more in-depth the heat transfer and fluid flow in the surrounding ground, which facilitates more accurate simulation results (Ochs, 2014, 2015b). In this context, Dahash et al. developed a numerical multi-physics TES model as part of "*giga_TES*" project. The model is developed in COMSOL Multiphysics® and capable to capture the different geometrical options (e.g. tank, cone, pyramid) as shown in Fig. 5. It is noteworthy to mention that COMSOL Multiphysics interprets the system of partial differential equations via FEM and solves it via advanced numerical methods.

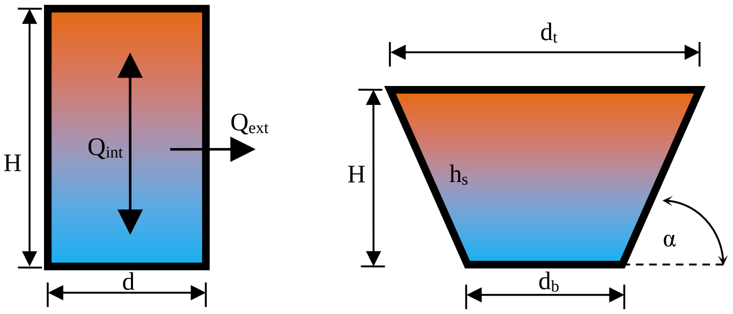

**Fig. 5: Geometry of a seasonal thermal energy storage with internal and external losses: (a) tank, (b) pit (Dahash et al., 2020a).**

### 3.2 Validation of the developed component-level model

In order to gain trust in the results of a transient model, it is important to compare the model results against measured data. Thus, the Dronninglund pit TES in Denmark was chosen as a case study for validating the developed model in COMSOL Multiphysics (Sørensen and Schmidt, 2018). This pit TES has a volume of approximately 60,000 m$^3$ and presented in Fig. 4. Thus, Table 1 provides an overall energy balance for the Dronninglund PTES in which a comparison between simulated (cone PTES, pyramid PTES) and measured energy is revealed.

In Table 1, the pyramid PTES is a 3-D numerical model and corresponds exactly to the Dronninglund PTES from a geometric point of view, whilst the cone PTES is an axisymmetric 2-D model and represents the adaptation of Dronninglund into a conical geometry. Concerning the charging/discharging energy, the model "pyramid PTES" provides results slightly closer to measurements than those of the cone, whereas the simulated outcome for the change in internal energy ($dQ$) deviates in both cases by 2 MWh. Given a deviation lower than 3 % for both models in comparison to the measurements, it is held that both models are reliable. Further information concerning the developed model and its validation can be found in (Dahash et al., 2020a).

Fig. 6 depicts the breakdown of charging/discharging energy for the Dronninglund PTES in which the simulated monthly energy is compared to that of the measurement. Therein, the positive values stand for energy charged into PTES, whereas the negative values represent the energy discharged out of PTES. Apparently, the error is below 2 % over most of the year 2015. However, this is not true for November of the simulated year as a remarkable error in the charging energy is observed for both models. It is held that this error is primarily originated due to the low measured charging energy during November against which any small difference between the measured and simulated values might lead to an apparent error.

**Table 1: Simulated and measured energy flows for Dronninglund PTES (reproduced from (Dahash et al., 2020a)).**

| | **Charging Energy** | **Discharging Energy** | **Internal Energy** | **Thermal Losses** | | | | **Efficiency** | |
|---|---|---|---|---|---|---|---|---|---|
| | $Q_{\mathrm{ch}}$ | $Q_{\mathrm{dis}}$ | $dQ$ | $Q_{\mathrm{top}}$ | $Q_{\mathrm{side}}$ | $Q_{\mathrm{bot}}$ | $Q_{\mathrm{loss}}$ | $\eta_{\mathrm{I}}$ | $\eta_{\mathrm{II}}$ |
| | **[MWh]** | **[MWh]** | **[MWh]** | **[MWh]** | | | | **[-]** | |
| **Measurements** | 12 760 | 11 982 | -497 | 786 | - | - | 1275 | 0.9 | 0.76 |
| **Pyramid PTES** | 12 743 | 11 966 | -499 | 787 | 481 | 9 | 1276 | 0.9 | 0.76 |
| **$\varepsilon$ [%]** | 0.13 | 0.13 | 0.4 | 0.13 | - | - | 0.1 | 0 | 0 |
| **Cone PTES** | 12 741 | 11 962 | -495 | 788 | 478 | 9 | 1274 | 0.9 | 0.76 |
| **$\varepsilon$ [%]** | 0.15 | 0.17 | 0.4 | 0.25 | - | - | 0.1 | 0 | 0 |

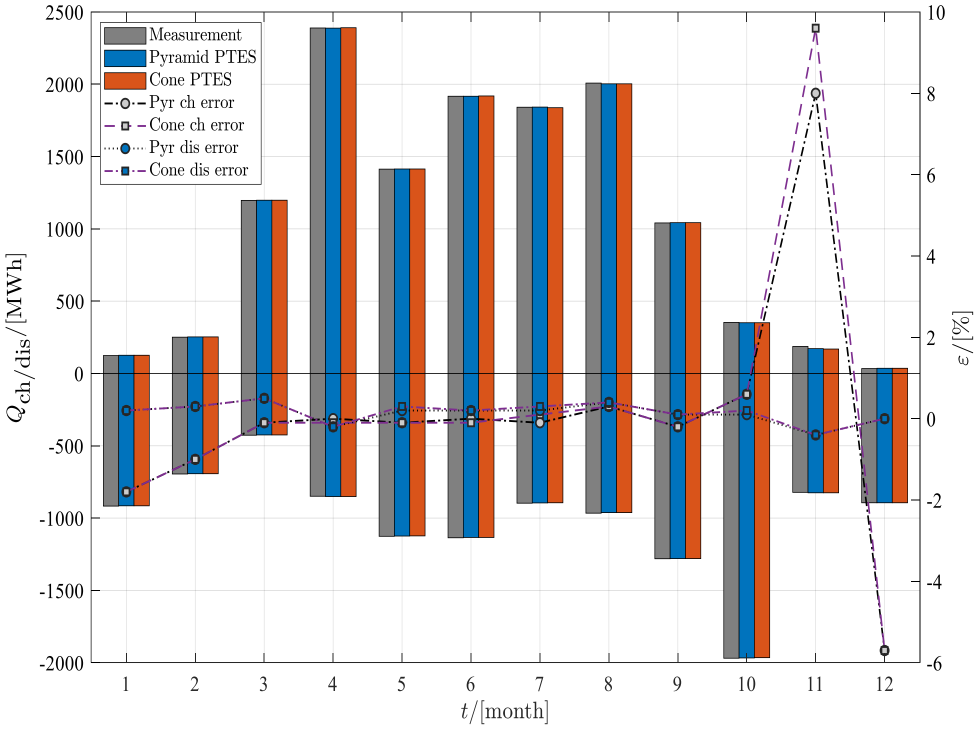

**Fig. 6: Breakdown of simulated charged (+)/discharged (-) energy into/from PTES compared to the measurement in the year 2015 (reproduced from (Dahash et al., 2020a)).**

Fig. 7 proves a remarkable matching between both simulated and measured PTES temperature for an array of heights from 16 m down to 0.5 m. Inevitably, it reveals that PTES reached a maximum temperature of around 89°C during summer (starting from day 230 to day 280). Throughout this period, PTES functioned as a short-term storage. Whereas for the period (60 – 180 days), PTES was into operation as multi-functional storage.

It is worthy to mention that the existence of groundwater in TES surroundings might eventually lead to higher thermal losses and, accordingly, higher temperatures in the ground. Therefore, it is of high importance to include the groundwater existence in the TES modeling. Thus, Dahash et al. (2019b) further extended the aforementioned developed model further to include the groundwater. The inclusion of groundwater aspect was validated against FEFLOW (Diersch, 2014), which is a well-established FE tool for groundwater simulations.

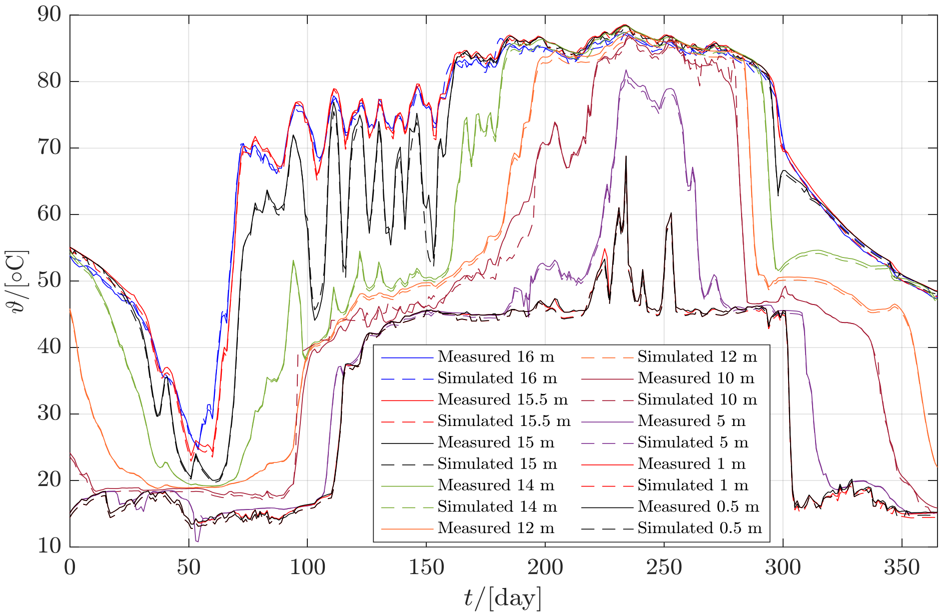

**Fig. 7: Development of PTES simulated and measured temperatures in the year 2015 with hourly resolution (reproduced from (Dahash et al., 2020a)).**

### 3.3 System-Level Modeling and Efforts to Couple System-Level Model with Component-Level Model

Numerical modeling tools (e.g. COMSOL Multiphysics) can accurately deliver robust analyses of buried TES and, subsequently, profound insights that enable optimizing the stores for an efficient design and operation. Yet, ESS tools are commonly used for system-level modeling in order to reduce the computation efforts. Such tools are TRNSYS, EnergyPlus, Modelica/Dymola, Matlab/Simulink and others. Compared to other ESS tools, TRNSYS is frequently seen as the widely-used tool when modeling buried water TES as its TES models can be easily coupled to buildings, heating plants and other components in a system level and also due its modular nature for adding further new components (Crawley et al., 2008). Nevertheless, there exist attempts to seek the modeling of buried TES in other environments. For instance, Ochs (2014) presents a dynamic FD model that is able to represent various construction shapes (cylinder, cone) for underground hot water TES in Matlab/Simulink environment.

Further, a dynamic model for a solar DH system with a seasonal TES was presented in (Kubiński and Szabłowski, 2019). The dynamic model was developed in Aspen HYSYS software to represent the S-DH systems in Vojens, Denmark. Given the fact that this tool offers only cylindrical tanks, the PTES installation in Vojens was approximated to a tank with same upper circumference and volume of the actual TES. Another drawback in the tank model is that it is a fully-mixed component and, thus, to tackle this challenge different tank elements were connected in series to develop a stratified tank. It is important to mention that the proposed modelling approach led to results significantly differ from the actual installation.

In an attempt to condense the computational efforts, van der Heijde et al. (2019a) utilized time aggregation algorithms (i.e. representative days) to represent an S-DH system equipped with a seasonal TES. It was revealed that the algorithm is computationally cheaper by 10-30 times when compared to simulations without aggregation. Yet, it was concluded that the minimum required number of representative days was not obtained. On a brighter note, the algorithm was recently used to determine the optimal design and control of a fictional district energy system of the city of Genk, Belgium (van Der Heijde et al., 2019b).

In Modelica/Dymola, there exist a number of TES components that are used for investigation purposes. For instance, there exist different configurations of TES in Modelica Buildings library (Wetter et al., 2014) such as: TES with internal heat exchanger, TES without heat exchanger and others. These models were validated in different research studies. Yet, these models were limited to small-scale TES (residential buildings TES with ~ 1 $m^3$ up 3 $m^3$). Thus, different system-level TES components are developed for large-scale TES in Modelica/Dymola tool within the framework of giga_TES project and they are being investigated for calibration purposes. Yet, these models are characterized with a major shortcoming as they are capable to only represent tanks. In this context, Dahash et al. (2020b) presented the development of Modelica buildings library TES models for large-scale TES simulations. Further, the work developed a 2-D soil domain using FD discretization in order to simulate underground large-scale TES. The model was cross-validated against the aforementioned COMSOL model and, then, used for TES design optimization.

Given the importance of accurate multiphysics in modeling underground TES, and the less computation efforts seen by ESS tools, it is quite often to integrate a component-level model into a system-level model. This steers the efforts to couple ESS tools (e.g. TRNSYS) with accurate multiphysics tools (e.g. COMSOL Multiphysics) forming the so-called (ESS-HAM) or (ESS-hygrothermal) coupling (Ferroukhi et al., 2017 and van Belleghem et al., 2011). This approach delivers detailed performance analysis for the energy system (e.g. TES) with simulation of heat, moisture and air (HAM) transfer and, subsequently, it provides comprehensive modeling of the envelope domain (e.g. TES wall, insulation and liner) (Cóstola et al., 2009).

Accordingly, Fig. 8 shows an exemplary overview for a co-simulation process in which a detailed TES model is developed in a multiphysics tool and coupled to an ESS tool. In this process, the TES model consists of TES envelope domain with fluid domain. The calculation procedure used for the multiphysics tool could be identical or different to that used in an ESS tool. This schematic overview represents a possible co-simulation platform used for a large-scale TES system that is buried in the ground.

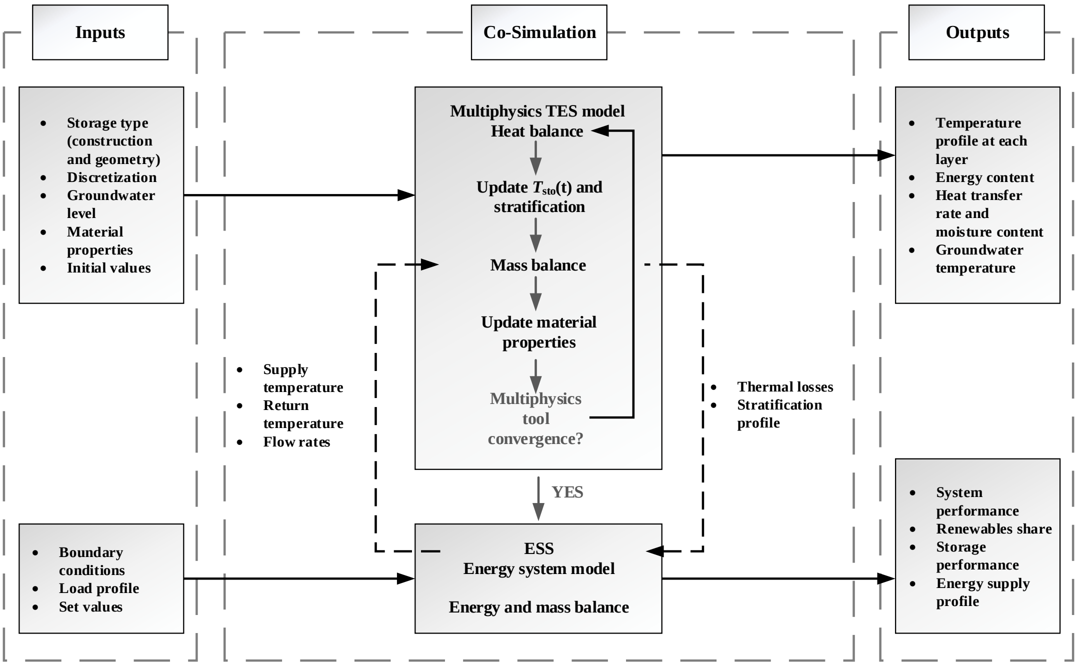

**Fig. 8: An exemplary schematic overview for a co-simulation platform for developing a large-scale buried TES (reproduced from (Dahash et al., 2019a)).**

Material properties, groundwater level, discretization mode, storage type and initial values are all together given as inputs to the multiphysics tool, whereas boundary conditions, load profiles (e.g. heat load, supply and return temperature, flowrates) and set values are inputs for ESS tool. The co-simulation process starts at a time step (t) with running the simulation for the TES model in multiphysics tool and, then, the values (thermal losses and stratification profile) are extracted and transferred to ESS tool. Next, ESS tool runs the simulation for the overall energy system considering accurate thermal losses and temperature profiles for TES. Thus, the ESS tool computes accurate values for the energy system and, then, it exchanges temperatures (supply and return), flowrates and load profiles with the multiphysics tool. Therefore, in the next time step (t+1) the multiphysics tool is able to compute again the values and exchanges it with ESS tool. This process is repeated for a required investigation time (e.g. 5 years) and, later, each model delivers different outputs. For the multiphysics tool, the outputs are temperature and energy content at each layer, moisture transfer rate to the surroundings and groundwater temperature. Whereas the outputs for ESS tool are renewables share, system and storage performance and energy supply profile.

Inevitably, it is important to pinpoint that the co-simulation process given in Fig. 8 is an example for a possible coupling between an ESS tool and a multiphysics one and the process is not necessarily limited to those. Other possible co-simulations can be set up between different tools and following different algorithms. Another experience, for example also not limited, is the co-simulation between a CFD tool (e.g. ANSYS Fluent) and a multiphysics tool. In such a coupling, the fluid domain (i.e. water) and the thermo-hydraulic behavior (e.g. stratification, buoyancy) are fully developed in the CFD tool, whereas the TES envelope (e.g. walls, insulation and liners) are implemented in a multiphysics tool. This process also produces valuable analysis regarding the heat transfer performance between the fluid and envelope domains. Therefore, it is highly recommended to underline the goal of co-simulation so that the tools that serve the required goal can be short listed.

Additionally, another successful proposal for co-simulation environments is the TISC suite, which makes possible to couple some simulation tools. This software package succeeds in connecting a numerical modelling tool (i.e. COMSOL Multiphysics) with ESS tool (i.e. Modelica/Dymola) and it consists of a simulation package and control package and, therefore, this makes it possible to run simulation for three or more partial simulations (TLK-Thermo GmbH, 2019). Another successful technique is the functional mock-up interface (FMI) tool, which is a standard option for supporting dynamic model exchange and co-simulation (Blochwitz et al., 2011). Besides, building controls virtual test bed (BCVTB) is also sometimes experienced for coupling different simulation tools enabling a co-simulation environment. This software environment permits, additionally, to couple the simulation tools with existing hardware (Wetter and Haves, 2008).

Yet, it is noteworthy to highlight the gap seen between the two levels of modeling in spite of the few aforementioned studies. Hence, it is remarkably important to create a well-established linking platform for large-scale underground water stores detailed models coupled into energy system simulation tools, rather than standing-alone models (either detailed or coarse models).

## 4. Conclusion

Seasonal thermal energy storage systems are prominent elements for renewable-based district heating systems. Yet, the large volumes and the corresponding investment costs are key obstacles that hold this technology from being experimentally examined. Therefore, simulation-driven assessments are crucial to investigate these systems. Accordingly, this work reported the recent advances in modeling of large-scale TES. The work illustrated the TES modeling hierarchy process as it is categorized into: pre-design, detailed design, technology integration, evaluation and optimization. The work reported the different models used in each step of the modeling process hierarchy.

Further, the work documented a synopsis of research studies highlighting the advantages and pitfalls of the existing TES models. Thus, the work reported the TES modeling development within the international project (Giga_TES). A component-level TES model was implemented in COMSOL Multiphysics and validated against measured data from Dronninglund pit TES in Denmark. The numerical model was further extended to include the groundwater aspects in order to permit the inspection of groundwater influence on TES operation. Moreover, the work discussed the development of different coarse models that are appropriate for system simulations in Modelica/Dymola. Yet, the major downside of the coarse models is that they are capable to represent tanks only. Thus, future work will focus on further development of Modelica/Dymola TES models to represent other TES geometries (e.g. cone, pyramid).

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