High-temperature aquifer thermal energy storage integration into a geothermal-powered district heating system: a case study from the German Molasse Basin

Kalliopi Tzoufka[1], Kevin Bock[2], Guido Blöcher[3,4], Laura Lehmann[2], Mauro Cacace[3], Daniela Pfrang[1,5], Clemens Felsmann[2], Kai Zosseder[1]

[1] Technical University of Munich, Department of Civil and Environmental Engineering, Geothermal Energy Group, 80333 Munich, Germany

[2] Technical University of Dresden, Institute of Power Engineering, Chair of Building Energy Systems and Heat Supply, 01062 Dresden, Germany

[3] GFZ Helmholtz Centre for Geosciences, 14473 Potsdam, Germany

[4] Technical University of Berlin, Department of Engineering Geology, 10587 Berlin, Germany

[5] SWM Services GmbH, 80992 Munich, Germany

kalliopi.tzoufka@tum.de

Keywords: High-Temperature Aquifer Thermal Energy Storage (HT-ATES), District Heating Network (DHN), numerical modelling, system co-simulation, North Alpine Foreland Basin.

ABSTRACT

High-Temperature Aquifer Thermal Energy Storage (HT-ATES) has the potential to enhance the flexibility of energy systems and to contribute to the transition toward decarbonized heat supply schemes. In this work, we present a numerical analysis of a multicomponent energy network integrating HT-ATES. A small-scale District Heating Network (DHN) from the area of Munich, Germany, serves as our case study. In the current system configuration, a geothermal plant exploiting the Lower Cretaceous/Upper Jurassic geothermal reservoir (North Alpine Foreland Basin) provides the base load, while a gas boiler unit covers the peak heat demand. This study focuses on the development of a seasonal HT-ATES system into the geothermal reservoir and its integration into the investigated energy network. To further enhance the overall energy flexibility of the multicomponent system, a short-term Thermal Energy Storage (TES) tank is additionally introduced. The proposed hybrid storage system aims to satisfy the peak heat demand and consequently to partially replace the conventional fossil-fuelled gas boilers. We develop a numerical model to simulate the thermal-hydraulic behaviour of the HT-ATES system. In addition, the DHN and TES systems are simulated using a thermal-hydraulic model with actual customer heat consumption data. Our simulation results demonstrate that the integration of HT-ATES together with the TES component into the investigated energy system can cover a significant proportion of the peak demand, thus reducing the usage of the conventional fossil-fuelled heat generator.

1. INTRODUCTION

Multicomponent energy systems and their flexible operation emerge as a critical approach to reducing the share of conventional fossil-fuelled heat generation and consequently decarbonizing District Heating Networks (DHN). These hybrid systems rely on the integration of various technologies to enhance the energy flexibility of DHNs. Such methodologies, capable of shifting energy and thus of balancing the temporal supply-demand mismatch, are Thermal Energy Storage (TES) approaches, including both long-term seasonal and short-term heat storage. In particular, High-Temperature Aquifer Thermal Energy Storage (HT-ATES), operated in a seasonal mode, has the potential to enhance the energy redistribution within the energy network. In these systems, the reservoir rock and fluid serve as the heat storage media.

In the area of the German Molasse Basin (North Alpine Foreland Basin), one of Europe's most developed geothermal provinces, efforts are consistently directed toward the decarbonization of the heating sector primarily through geothermal energy resources. Concurrently, the storage of thermal energy in the subsurface is gaining increasing attention as an indispensable component of future energy systems. Particularly in the greater area of Munich, the synergy between large amounts of excess energy and the existing or under planning DHNs capable of utilizing the stored thermal energy provides an ideal basis for HT-ATES implementation. To assess this concept, a case study tailored to the German Molasse Basin is performed, based on the intensively exploited Lower Cretaceous/Upper Jurassic geothermal reservoir and a local district heating system. The latter consists of a geothermal plant as its primary heat source component and an additional gas boiler unit deployed to cover peak loads and ensure redundancy.

In this work, we present our initial approach, in which we numerically integrate the HT-ATES system into the case study energy network. The HT-ATES system aims to cover peaks in the heat demand and consequently reduce the load on the fossil-fuelled heat generation unit. In this respect, the HT-ATES system is designed to supply heat on a seasonal basis, thus contributing transiently only during the high-demand period and supplementing the operating geothermal plant in the overall heat supply. To further enhance the overall energy flexibility, we introduce an additional TES tank into the energy system, which serves as a short-term heat storage component. We develop a multiphysics numerical model for the HT-ATES system to simulate the storage of high-temperature fluids into the Lower Cretaceous/Upper Jurassic geothermal reservoir in the greater area of Munich. Simultaneously, we perform a thermal-hydraulic simulation of the DHN and the TES components. The coupling of these distinct models is performed through the exchange of time series of both mass fluxes and fluid temperatures between the different modelled systems.

2. PROBLEM FORMULATION

Geothermal energy has been successfully harnessed in the German Molasse Basin for more than two decades. Currently, 25 active geothermal plants exploit the hydrothermal resource originating from the Lower Cretaceous/Upper Jurassic geothermal reservoir, and supply heat to the local energy networks. In a direction toward decarbonized heating, local operators are increasingly focusing on the flexible operation of the energy networks and the replacement of fossil-fuelled heat supply. Concepts of HT-ATES, which enable energy redistribution and can provide the required heat to cover peaks in the heat demand, are considered primary candidates to promote this transition. However, achieving high overall system efficiency requires the successful integration of HT-ATES through an optimal operational design of the different components of the energy network.

2.1 Case-study energy system

An energy system from the greater area of Munich (southern Germany) is considered in this study. Compared to other networks in the metropolitan area of Munich, the case study DHN is a small-scale network, with a pipeline length of approx. 48 km and around 200 consumers.

The temperature in the supply line of the DHN ($T_{DHN,supply}$) ranges from 72 to 94 °C, in dependence to the local atmospheric temperature, while the return line temperature is 45 °C. The principal heat source in this energy system is a geothermal plant. This consists of a well doublet that reaches depths of up to 2,200 m and exploits the hydrothermal resource of the Lower Cretaceous/Upper Jurassic geothermal reservoir. The produced reservoir fluid at a temperature of ca. 74 °C covers the base load of the DHN. After heat extraction, the produced formation fluid is reinjected into the reservoir at 45 °C. In addition to the geothermal plant, multiple gas boilers are used to cover peaks in the heat demand and provide redundancy.

The data used in this study reflect the fluctuating heat demand and correspond to actual customer heat consumption from the case study DHN over one operational year. They reveal an average heat load of approx. 9 MW, with peaks in the heat demand that reach up to 17.5 MW. The total annual peak load amounts to 4.4 GWh/a and is currently supplied by the gas boilers.

2.2 Multicomponent system configuration

In the present study, we investigate the integration of an HT-ATES system into a DHN. The primary objective is to reduce reliance on fossil-fuelled heat supply by introducing HT-ATES into the case study energy system. However, gas boilers are characterized by their ability to respond rapidly to sharp fluctuations in the energy demand. In contrast, HT-ATES compose elements of seasonal thermal energy storage, operated in a more stable manner. Our preliminary numerical analysis showed that with integration of the HT-ATES system alone, only a small proportion of peak load is covered by the stored thermal energy. In turn, this further leads to a low amount of heat extracted from the HT-ATES, consequently compromising over time the thermal performance of the heat storage operation.

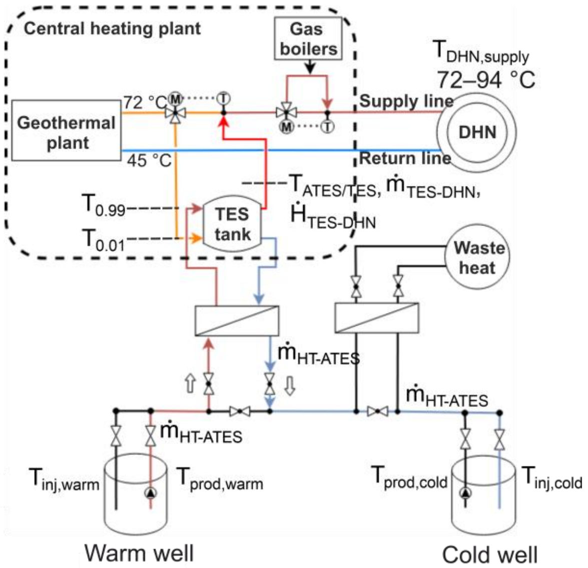

Figure 1: Configuration of the multicomponent system with the central heating plant consisting of the geothermal plant, the TES tank, and the gas boilers. The HT-ATES system together with the TES component are introduced to cover peaks in the heat demand.

To address these challenges and to further enhance the energy flexibility in the system, we propose the incorporation of an additional TES tank. Therefore, we consider four primary components (Fig. 1) for flexible heat distribution and operation of the energy network: (1) the geothermal plant, (2) the gas-boiler unit, (3) the

HT-ATES system for seasonal heat storage, and (4) an intermediate TES tank for short-term heat storage.

A schematic of the multicomponent system configuration is shown in Fig. 1. Based on the acquired heat load curve of one year, we define two successive operational phases. Hereafter, we refer to the “low-demand period” as the time interval from the beginning of May to the end of October, while the “high-demand period” covers the interval from the beginning of November to the end of April. The geothermal plant supplies the base load throughout the year, maintaining 72 °C in the supply line of the DHN.

During the low-demand phase, the HT-ATES system is charged by recovered waste heat, while the TES tank remains inactive. In the subsequent high-demand period, the HT-ATES system is discharged, charging simultaneously the intermediate TES tank. In this system configuration, the HT-ATES system charges continuously the TES component through a heat exchanger at a constant mass flow throughout the high-demand period. The primary objective is that the TES tank holds sufficient thermal energy to efficiently respond to short-term variations in the peak load. In turn, thermal energy is discharged from the TES tank as soon as the DHN heat demand increases, transferring the energy into the supply line of the network.

In the proposed system configuration, the TES tank functions as both a connection and a buffer element between the HT-ATES system and the DHN. The TES component has two double ports, each consisting of one inlet and outlet (Fig. 1). One double port connects the HT-ATES system to the TES tank. The second double port connects the TES tank to the supply line of the DHN.

3. METHODS

The problem requires the definition of two numerical models for the distinct systems. A multiphysics numerical simulation of the HT-ATES system has been performed to capture the thermal-hydraulic effects in the Lower Cretaceous/Upper Jurassic geothermal reservoir induced by the heat storage operation. In addition, a thermal-hydraulic model of the DHN and the TES tank has been developed for this specific application. The coupling of the modelled components is performed through the exchange of time series of both the operational mass fluxes and the fluid temperature between the disparate systems over one operational year.

3.1 HT-ATES numerical model

The coupled thermal-hydraulic numerical simulation of the HT-ATES system has been performed using the open-source numerical simulator GOLEM (Cacace and Jacquey, 2017). Computation results provide the primary state variables pore fluid pressure p_f, and temperature T. In addition, pressure and temperature dependence of the fluid density and fluid viscosity are accounted for through thermodynamically consistent Equations of State (EOS) (IAPWS, 2018a, b).

The HT-ATES numerical model is based on three geothermal plants which operate in the Lower Cretaceous/Upper Jurassic geothermal reservoir in the area of Munich. In this respect, the model is constrained by the in-situ reservoir rock properties. The model geometry, spatial discretization as well as the assigned material properties and fluid properties are described in detail in Tzoufka et al. (2024). Both vertical wells intersect only the upper 50 m of the geothermal reservoir (Fig. 2).

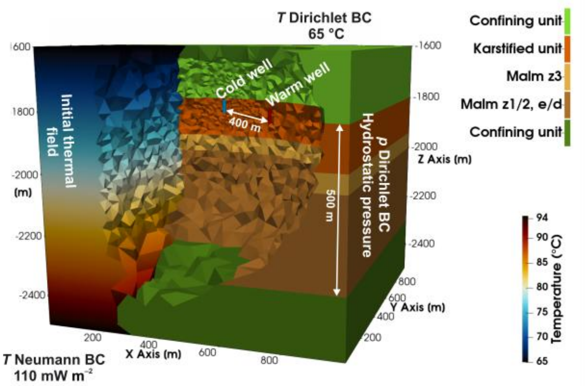

Figure 2: 3D finite element model of the HT-ATES system, displaying the model units, the wells of the heat storage operation, and the spatial discretization. Thermal and hydraulic BC’s as well as the initial thermal field are also displayed.

The model presented in Tzoufka et al. (2024) has been modified to reflect the in-situ reservoir conditions of the investigated area. Accordingly, we constrain the top of the model domain with a constant Dirichlet Boundary Condition (BC) for the temperature equal to 65 °C (Fig. 2). Similarly, the operational design of the seasonal heat storage is also adjusted according to the heat requirements of the case study DHN. In this configuration, the injection and production flow rates ($\dot{m}_{HT-ATES}$) in both wells are kept constant and equal to 14 kg s^{-1}. The storage of high-temperature fluid occurs through the “warm well” at 100 °C over 6 months (i.e., the HT-ATES charging phase). During the subsequent 6 months (i.e., the HT-ATES discharging phase), the stored fluid volume is produced from the warm well. After heat extraction, the produced fluid is reinjected into the “cold well” at 74 °C. The heat storage operation is simulated over a total period of 10 years. The assigned time stepping scheme ranges from 5 seconds at the start of the computation as well as of each transition in the operation mode, gradually increasing to time-steps of up to 2 weeks.

3.2 DHN and TES tank numerical model

The DHN is simulated with a thermal-hydraulic network model using the code TRNSYS-TUD (Perschk, 2000). An additional module implemented within TRNSYS-TUD for the TES component simulates the temperature distribution within the tank and heat losses from this component (Kaiser, 2013).

The DHN structures are parameterized in detail with relevant pipe characteristics (i.e., pipe dimensions and pipe material), hydraulic features (i.e., pressure losses due to pipe geometry and due to additional structural elements of the grid) and other network components such as pumps and valves. In addition to the geometric network data and hydraulic parameters, additional input parameters include the customer data (e.g., heat load), the corresponding local atmospheric temperature, and the mass flux and fluid temperature of the cold and warm well of the HT-ATES simulation.

A thermal-hydraulic simulation is performed for the parameterized grid structure over a period of one year with time-steps of 1 minute. The model of the local DHN developed in this study provides the transient accumulated annual load curve for the actual network characteristics (pipe properties and network geometry) as well as additional system-dependent physical parameters.

The TES is assumed to have a cylindrical shape, with a size of 20,000 m^3, in reference to comparable existing storage tanks. Relative heat storage losses, such as surface heat losses, are calculated directly in dependence to the local annual atmospheric temperature.

3.3 Coupling of the modelled systems

Initially, the HT-ATES simulation is performed. Numerical results include the temperature evolution in the cold and warm well of the HT-ATES over the entire simulation period. For the coupling of the two systems, the assigned mass flux and the computation results from the last year of the heat storage operation (i.e., the 10th year) are utilized. These results are adjusted to the 1-minute time-steps required by TRNSYS-TUD and serve as input for the DHN and TES simulation.

The coupling of the HT-ATES with the DHN and TES modelled systems is performed with a simulation over one year with 1-minute time-steps. It is worth noting that in the DHN and TES simulation, physically inconsistent operational conditions (e.g., unrealistically high mass fluxes) are intercepted by implementing temperature and mass flow limitations in the model.

4. NUMERICAL RESULTS

The supply temperature in the DHN from the different heat source components over the simulated year is shown in Fig. 3. These components include: (1) the geothermal plant, which maintains 72 °C in the DHN supply line throughout the entire year, (2) the combined ATES/TES heat storage system, representing the temperature after the TES component, and (3) the gas boilers, which supply additional heat in phases when the stored thermal energy in the TES tank is not sufficient to satisfy the heat demand. The temperature evolution in Fig. 3 distinctly reflects the increased heat requirement during the high-demand period, while in parallel it exhibits a sharp fluctuation over this time.

These results show that during the low-demand phase, the operation of the geothermal plant is in principle sufficient to supply the required thermal energy and to maintain 72 °C to the DHN. During this period, the HT-ATES system is charged, while the TES tank remains inactive. Consequently, the sporadic individual peaks in demand during this phase (e.g., in September) are covered by the gas boiler unit.

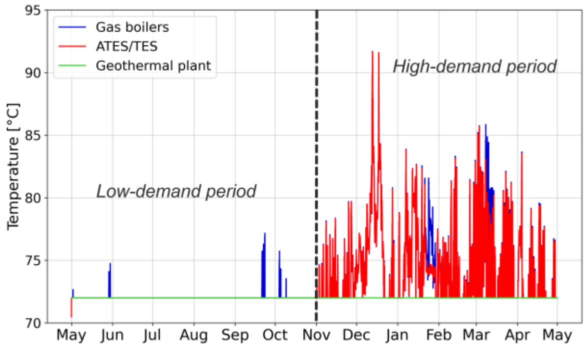

Figure 3: Simulated supply temperature in the DHN over the simulation based on the different heat source components, including the geothermal plant, the gas boilers, and the hybrid HT-ATES and TES storage system.

At the beginning of November, the thermal energy discharged from the HT-ATES starts charging the intermediate TES tank. Simultaneously, as heat demand increases, the TES tank contributes to covering the fluctuating peak load of the DHN. The results reveal that the hybrid HT-ATES and TES system responds to the short-term fluctuation in the load curve and covers a substantial fraction of the peak load. However, there are periods of temporary high demand when the hybrid HT-ATES and TES system is unable to cover the peak load. The remaining required heat must be supplied by the gas boilers (e.g., in mid-January). Yet, the combined HT-ATES and TES storage system covers a significant proportion of the peak demand.

Fig. 4 illustrates the computed temperature of the fluid volume in the TES component at different heights of the tank, with the subscripts corresponding to percentile height of the tank. We further cross-plot the mass flux ($\dot{m}_{TES-DHN}$) from the TES tank to the DHN. During the low-demand phase, when the HT-ATES is charged, the TES unit is inactive, and thus the temperature therein declines along its entire length due to heat losses.

With the increase in demand at the beginning of November, heat is transferred from the TES tank to the supply line of the DHN. The magnitude of the mass flux reflects the rate of heat transfer from the TES component to the DHN. The graph shows that during periods of low-magnitude mass flux, the temperature of the deeper layers of the TES tank gradually rises. This period corresponds to a relatively low peak load. This system response is for instance particularly evident in November, when the mass flow toward the DHN remains limited. By mid-November, the deepest layer of the TES tank is also impacted by this temperature increase.

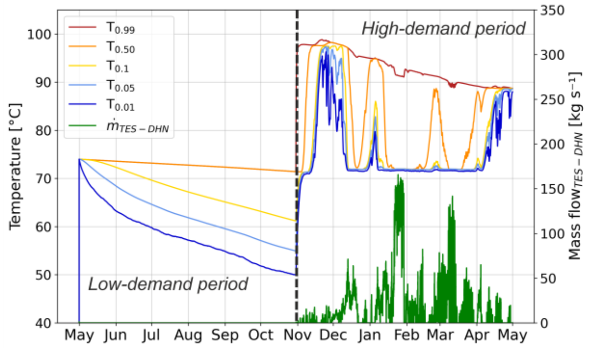

Figure 4: Simulated temperature development in the TES component at different percentile heights of the tank and computed mass flux from the TES tank to the DHN over the entire computation.

In turn, when the first sharp peak in the heat demand occurs, reflected by a steep rise in mass flux, the temperature decreases throughout the entire TES tank. The results further show that once the mass flux declines again, the temperature within the tank gradually recovers. We further observe that the top of the tank, represented by $T_{0.99}$, experiences the lowest fluctuation in magnitude. This is due to the fact that the TES tank is continuously charged by the HT-ATES system at this height. The magnitude of temperature fluctuations increases with depth due to slower thermal energy replenishment.

In Fig. 5, we cross-plot the computed fluid temperature in the warm ($T_{warm,well}$) and cold ($T_{cold,well}$) well of the HT-ATES system, together with the heat flux ($\dot{H}_{ATES-TES}$) from the HT-ATES system to the TES tank. During the charging period of the HT-ATES, the fluid temperature in the warm well stabilizes at the imposed 100 °C, whereas during the subsequent discharging phase it exhibits the typical declining trend observed in HT-ATES systems. This behaviour is attributed to the conditioning of the reservoir.

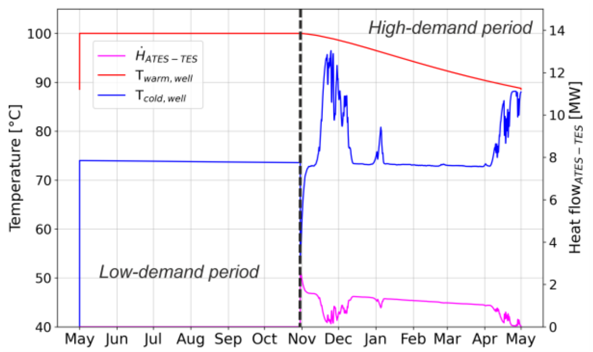

Figure 5: Simulated temperature evolution in the warm and cold well of the HT-ATES system and computed heat flow from the HT-ATES system to the TES tank over the entire computation.

Fig. 5 shows that during the high-demand period, the temperature in the cold well fluctuates, reaching a maximum value of approx. 96 °C. The simulated fluid temperature exhibits an inverse relationship to the heat flux from the HT-ATES to the TES. This system response occurs because, during phases of low heat demand in the DHN, less thermal energy is withdrawn from the TES tank. Consequently, the temperature of the fluid within the TES component gradually increases along its entire height, eventually impacting the deepest layers of the tank (Fig. 4). These layers correspond to the fluid volume directed to the heat exchanger between the TES and the HT-ATES system.

In Fig. 6, we present the total annual amount of thermal energy required to cover the peaks in the heat demand, corresponding to 4.4 GWh/a. We additionally show, after integration of the storage components, the fraction of the peak load covered by the combined HT-ATES and TES system ($Q_{ATES/TES}$), as well as the remaining share supplied by the gas boilers ($Q_{gas\ boilers}$). Our results indicate that, with the proposed multicomponent system configuration, 4.05 GWh/a can be provided by the introduced hybrid HT-ATES and TES system, while the contribution of the gas boilers decreases to 0.35 GWh/a. These results demonstrate that the integrated HT-ATES and TES system can cover the greatest proportion of the peak demand, corresponding to approx. 92 % of the annual peak load.

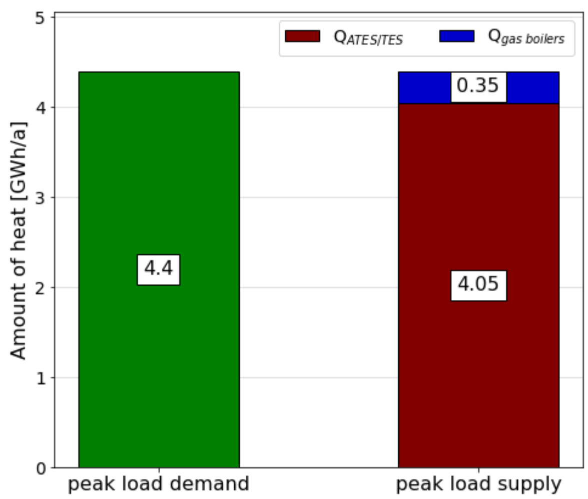

Figure 6: Total annual amount of thermal energy required to satisfy peaks in the heat demand, and proportions supplied by the combined HT-ATES and TES ($Q_{ATES/TES}$) system, and the gas boilers ($Q_{gas\ boilers}$) after integration of the heat storage components.

5. CONCLUSIONS

In this study, we present a methodology toward the decarbonization and flexible operation of a multicomponent energy system in the greater area of Munich. In the current energy network configuration, a geothermal plant comprises the primary heat source, while gas boilers cover peaks in the heat demand. The primary objective is to minimize the usage of the fossil-fuelled heat generator. To this end, we introduce an integrated storage system consisting of an HT-ATES system and an additional intermediate TES tank. The HT-ATES is operated in a seasonal mode and charges the TES tank, which in turn is responsible for covering the short-term fluctuations in the peak load.

We develop and couple thermal-hydraulic numerical models of the different system components. The computation results reveal that the proposed multicomponent system can be operated flexibly and cover the greatest proportion of the fluctuating peak heat demand. Our numerical analysis, therefore, demonstrates that the combined implementation of the HT-ATES system and the TES component has the potential to significantly reduce reliance on the fossil-fuelled heat source and decarbonize the energy system. Future research will focus on further optimizing the operational design of the multicomponent system. The main objective is to minimize non-utilized heat from the HT-ATES system and to further decrease the need for fossil-fuelled heat supply.

REFERENCES

Cacace, M. and Jacquey, A.B.: Flexible parallel implicit modelling of coupled thermal–hydraulic–mechanical processes in fractured rocks, *Solid Earth*, 8(5), (2017), 921–941. https://doi.org/10.5194/se-8-921-2017

IAPWS: Release on the IAPWS Formulation 2008 for the Viscosity of Ordinary Water Substance, Tech. rep., IAPWS, (2008a). http://www.iapws.org

IAPWS: Release on the IAPWS Formulation 2008 for the Thermodynamic Properties of Seawater, Tech. rep., IAPWS, (2008b). http://www.iapws.org

Kaiser, J.: TRNSYS-TUD - TYPE075 - Weiterentwicklung eines Modells für einen indirekt beheizten Speicher-Wassererwärmer / Pufferspeicher, interne Dokumentation, TU Dresden, Institut für Energietechnik, Professur für Gebäudeenergietechnik und Wärmeversorgung, (2013).

Perschk, A.: Gebäude-Anlagen-Simulation unter Berücksichtigung der hygrischen Prozesse in den Gebäudewänden, Dissertation, TU Dresden, (2000).

Tzoufka, K., Blöcher, G., Cacace, M., Pfrang, D. and Zosseder, K.: Physics-based numerical evaluation of High-Temperature Aquifer Thermal Energy Storage (HT-ATES) in the Upper Jurassic reservoir of the German Molasse Basin, *Adv. Geosci.*, 65, 103–111, (2024). https://doi.org/10.5194/adgeo-65-103-2024

Acknowledgements

This research was supported by the German Federal Ministry of Education and Research (BMBF) under the grant number 03G0911 in the framework of the SpeicherCity research project.