PROCEEDINGS, 50th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 10-12, 2025
SGP-TR-229

Predictive Modeling of Heat Storage in TU DELFT Campus

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Keywords: HT-ATES, PUSH-IT, DARTS, Geothermal Energy, Reservoir Modeling

ABSTRACT

Heat demand varies significantly across seasons, being high in winter and minimal in summer, while renewable heat sources like geothermal wells provide a consistent year-round supply. Additionally, residual heat from data centers and industries often results in excess heat during the warmer months. To manage this seasonal mismatch, underground thermal energy storage (UTES) can be used to store excess heat generated in summer for use in winter. This strategy reduces energy waste and optimizes resource use, lowers costs, and enhances the reliability of heating systems. The EU-funded PUSH-IT project aims to overcome the seasonal mismatch between heat demand and generation from sustainable sources using high-temperature (HT) UTES through three different storage technologies: in aquifers - ATES, in borehole - BTES, and in abandoned mines - MTES. This study aims to evaluate the utilization of the HT-ATES system on the TU Delft campus, which serves as one of the project's pilot demonstration sites, and assess its storage efficiency. The reservoir modeling study was conducted using the open-source simulator Delft Advanced Research Terra Simulator (DARTS) to evaluate the impact of different injection strategies. Three operational scenarios were analyzed: a moderate and stable injection rate (742 m³/day), a higher injection rate with intermittent rest periods (1254 m³/day), and a sinusoidal flow pattern based on heat demand. The results indicate that a stable injection rate yields the highest storage efficiency, minimizing heat losses while maintaining effective heat recovery. In contrast, higher injection rates lead to increased thermal dispersion, whereas a variable injection pattern provides operational flexibility but requires careful management to sustain efficiency. As part of the pilot demonstration, new wells will be drilled on-site, providing additional subsurface data to refine the geological model and improve reservoir predictions. Moreover, future modeling efforts will integrate the reservoir model with surface facility components, such as heat exchangers and heat pumps, to develop a fully coupled system. These advancements will enable more representative simulations, ensuring that model predictions better reflect real-world HT-ATES operation.

1. INTRODUCTION

Decarbonizing the heating sector is a critical step in the global transition towards sustainable energy systems. In the Netherlands, nearly half of natural gas consumption is allocated to heating, making it a key area for emissions reduction (Vardon et al., 2024). Geothermal energy is one of the most promising renewable heat sources due to its ability to provide a continuous and reliable heat supply, independent of weather conditions (Bloemendal et al., 2020). However, one of the main challenges in utilizing geothermal and other renewable heating sources is the seasonal mismatch between heat supply and demand. Heat demand in urban areas typically peaks during winter, while renewable heat sources such as geothermal wells produce a relatively stable output throughout the year. Additionally, excess residual heat from industrial processes, data centers, and waste heat sources often goes unused, leading to inefficiencies (Bloemendal et al., 2020).

To address this imbalance, Underground Thermal Energy Storage (UTES) technologies have been developed. Among these, High-Temperature Aquifer Thermal Energy Storage (HT-ATES) is particularly promising, as it enables the storage of heat in deep aquifers at temperatures above 50°C (Drijver et al., 2019). HT-ATES systems store excess heat produced during summer and discharge it in winter, thus improving energy efficiency, reducing reliance on fossil fuels, and enhancing the economic viability of geothermal projects (Kallesoee & Vangkilde-Pedersen, 2019). Despite these advantages, HT-ATES deployment still faces technical and regulatory challenges, including thermal losses, groundwater protection concerns, and system integration with existing district heating networks (Bloemendal et al., 2020).

The PUSH-IT project, funded by the European Union, aims to demonstrate the feasibility of HT-ATES, BTES, MTES through large-scale pilot studies at selected sites across Europe (Bloemendal et al., 2020). One of these pilot sites is located at TU Delft, where a deep geothermal doublet system is currently under development (Vardon et al., 2024). This geothermal system, known as Geothermie Delft, is designed to supply heat to the TU Delft campus and parts of the city of Delft. The project incorporates an HT-ATES component to store excess geothermal heat during periods of low demand, which will then be utilized to supplement heating needs during colder months (Vardon et al., 2024).

This study investigates the feasibility and performance of an HT-ATES system at the TU Delft campus using advanced numerical modeling techniques. Specifically, the study evaluates the impact of different heat injection and extraction strategies on storage efficiency and system performance. Various operational scenarios, including moderate constant flow, high flowrate with intermittent rests, and demand-driven sinusoidal injection, are analyzed to determine the optimal strategy for maximizing heat recovery and minimizing energy losses. The insights gained from this research will contribute to the optimization and broader implementation of HT-ATES technology, supporting its role in the future of sustainable urban heating systems.

2. METHODOLOGY

2.1 Model Domain

The numerical model represents a subsurface domain extending 1,500 meters horizontally and 500 meters vertically, covering the targeted aquifer formations. The TU Delft campus is located in an area with multiple potential aquifers suitable for high-temperature aquifer thermal energy storage (HT-ATES). Based on feasibility studies (Bloemendal et al., 2020), two primary formations were considered for heat storage: The Maassluis Formation (MSz3, depth: ~130–190 m) and The Ommelanden Formation (Omm, depth: ~410–460 m). To optimize project feasibility and reduce drilling costs, the shallower Maassluis aquifer was selected for pilot demonstration in the project and used as the primary storage reservoir in this study. The stratigraphy of the study area consists of alternating aquifer and aquitard layers, influencing groundwater flow and heat transfer dynamics. Table 1 summarizes the key hydrogeological properties of the subsurface formations, including hydraulic conductivity (horizontal and vertical), formation thickness, and initial groundwater temperature. These values were calibrated to ensure consistency with site-specific hydrogeological properties derived from subsurface investigations at Technopolis and Delft train station (Bloemendal et al., 2020). Additionally, Figure 1 presents a 3D geological model, illustrating the distribution of these layers and their classification of hydrogeologic properties.

Table 1: Hydrogeological properties of the subsurface formations at the TU Delft campus (Bloemendal et al., 2020).

Name	zTop [m-mv]	zBot [m-mv]	kh [m/d]	kv [m/d]	Temperature [C]
HIc	0	16	0.0	0.0	10
KRz2,3	16	33	40.0	8.0	11
URz1,2,3,4,5	33	38	45.0	9.0	11
WAk1	38	46	0.097	0.032	11
PZWAz2	46	70	15.0	3.0	11
WAk2	70	75	0.066	0.022	12
PAWAz3	75	80	10.0	2.0	12
WAk3	80	87	0.014	0.005	12
PZWAz4	87	96	12.0	2.4	12
MSk1	96	109	0.011	0.004	12
MSz2	109	125	9.0	1.8	13
MSk2	125	130	0.012	0.004	13
MSz3	130	182	10.0	2.0	13
MSc	182	222	3.5	0.012	15
MSz4	222	240	5.0	1.0	15
OOk1	240	287	0.015	0.005	16
OOz2	287	313	6.0	1.2	17
Ooc	313	380	0.6	0.005	18
Oa3	380	410	0.6	0.005	18
Omm	410	460	15.0	3.0	19

The numerical model domain and grid structure are shown in Figure 2. To optimize computational efficiency, an uneven grid spacing approach was applied in all directions, enhancing resolution around well locations ($\Delta x=\Delta y=5m.$) while reducing grid density near the model boundaries ($\Delta x=150m$, $\Delta y=100m$). The model consists of a total of 806,400 grid cells, ensuring high accuracy in simulating thermal and hydraulic processes within the aquifer system. The storage system includes three hot wells and four warm wells (Figure 2). The hydrogeological layering of the model incorporates a minimum of three layers per unit, except for the reservoir horizon, where four layers are included. This layering configuration ensures a detailed representation of thermal conduction and fluid flow dynamics. Dirichlet-type boundary conditions were applied at the side boundaries of the model, maintaining constant hydraulic head and temperature values. The top and bottom boundaries of the model were assumed to be closed.

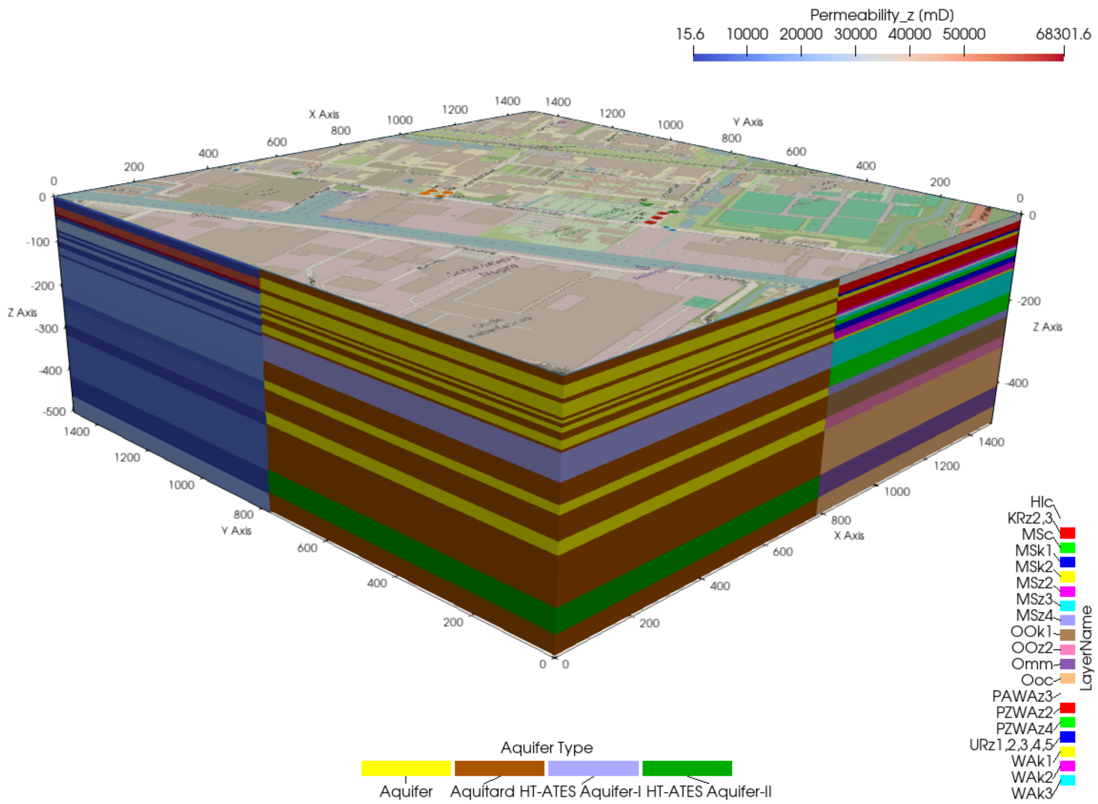

Figure 1: The 3D geological model of the TU Delft campus subsurface, illustrating the distribution of aquifers, aquitards, permeability variations, and formation names.

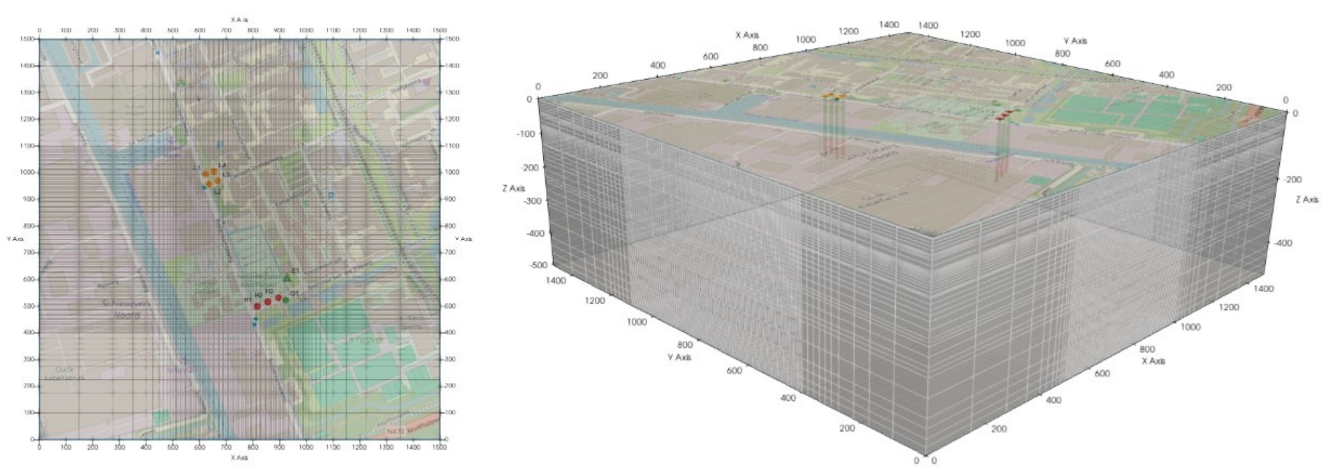

Figure 2: Numerical model domain and grid structure for HT-ATES simulations, with refined resolution near wells ($\Delta x = \Delta y = 5$ m) and coarser discretization at the boundaries ($\Delta x = 150$ m, $\Delta y = 100$ m).

2.2 Heat Storage Strategies

The HT-ATES system at the TU Delft campus is designed to store excess thermal energy generated by a deep geothermal doublet with an expected thermal capacity of 11.4 MW. This stored heat will be utilized to meet the heating demands of both the TU Delft campus and parts of the Delft district heating network. The anticipated annual heat demand profile for the district heating system, along with the projected thermal energy supply from the geothermal doublet, is presented in Figure 3-a. The difference between these two profiles represents the excess heat available for storage. Over the course of a year, the total storable thermal energy is estimated to be 32,082 MWh, assuming that excess heat accumulates over six months and is discharged over the remaining half of the year.

The storage process mainly consists of a charging phase, where hot water is injected into the reservoir at 90°C, a resting phase (scenario 2 only), where heat is retained within the aquifer, and a discharging phase, where stored heat is extracted. During heat extraction, the temperature of the withdrawn water from the warm wells is assumed to be 20°C, which is close to the initial aquifer temperature. Based on these temperature constraints, a total of 406,458 m³ of water is required for injection over the six-month charging period. Considering the three hot wells and four warm wells in the system, different operational strategies were developed to analyze their impact on temperature distribution in the reservoir and the storage efficiency of the system.

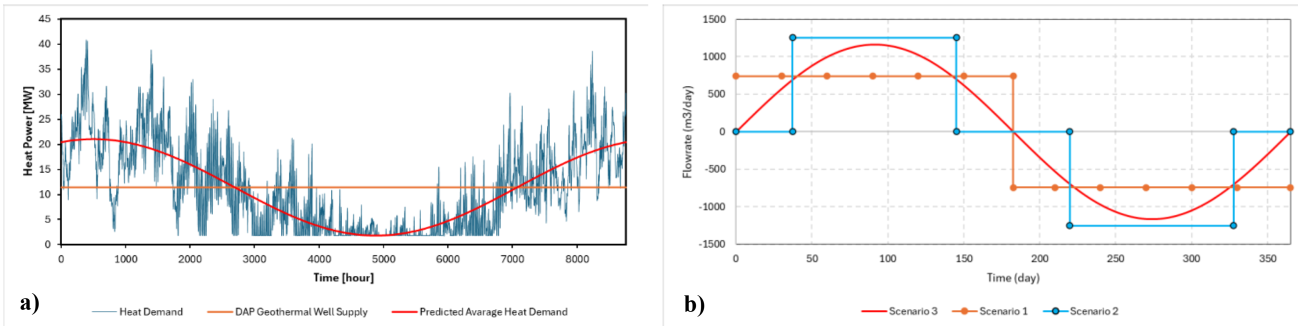

Figure 3: a) Annual heat demand profile for the TU Delft district heating system and thermal energy supply from the deep geothermal doublet (11.4 MW). The blue curve represents the hourly heat demand, while the red sinusoidal curve is the best-fit approximation of the seasonal heat demand trend. The difference between the geothermal supply and the predicted demand curve represents the excess heat available for storage in the HT-ATES system. b) Injection and production flow rate variations for the three operational scenarios. Scenario 1 follows a constant injection rate, Scenario 2 employs a high-rate injection with rest periods, and Scenario 3 applies a sinusoidal flow pattern based on dynamic heat demand.

The three scenarios investigated in this study are illustrated in Figure 3-b, which shows the variation of flow rates over time. In the first strategy, a stable injection rate of 742 m³/day per hot well was maintained throughout the six-month charging phase, followed by an identical extraction rate during the discharging phase. This approach ensured a uniform heat storage and recovery process, minimizing fluctuations in the reservoir. The second strategy aimed to investigate the effect of intermittent operation using the maximum feasible injection rate of 1,254 m³/day per hot well. This maximum rate was determined based on the well diameter (0.16 m) and screen length (52 m) to ensure that the flow velocity within the aquifer does not exceed 1 m/h, preventing mobilization of fine silt and clay particles that could clog the well screens. Instead of continuous injection, this scenario followed a cyclic pattern: an initial rest period of 37 days before 108 days of high-rate injection. A second rest period of 37 days completed the six-month heat storage phase. The same cyclic pattern was applied during the discharging phase, with heat extraction following the same rest-injection-rest sequence.

The third strategy introduced a dynamic operation, where injection and extraction rates were adjusted in response to heat availability and demand. Given that the heat demand profile exhibits an approximately sinusoidal pattern (Figure 3-a), a corresponding sinusoidal injection profile was calculated to match the required 32,082 MWh storage target over six months. This approach resulted in a peak injection rate of 1,166 m³/day per hot well, ensuring that all excess heat was captured in real time while maintaining the total injected water volume consistent with the other scenarios.

In all three strategies, the total injected water volume remained the same over the six-month charging period, ensuring a consistent basis for evaluating thermal recovery, heat losses, and overall system efficiency. The comparative analysis of these storage strategies provides insights into the influence of different injection patterns on long-term heat retention and operational flexibility in HT-ATES systems.

2.3 Delft Advanced Research Terra Simulator

The Delft Advanced Research Terra Simulator (DARTS) is employed in this study to model porous media heat flow, accounting for both convective and conductive heat transfer between fluids and the surrounding rock matrix (Voskov, 2017). In geothermal reservoir simulations, the fundamental governing equations encompass mass and energy conservation principles, incorporating assumptions regarding thermal equilibrium between the solid and fluid phases (Voskov & Tomin, 2019). A fully coupled, fully implicit numerical scheme is utilized, ensuring unconditional stability and accuracy (Voskov et al., 2021). DARTS applies a finite volume method (FVM) along with a two-point flux approximation (TPFA) to discretize the governing equations, facilitating robust and efficient simulations (Hajibeygi et al., 2011). The simulator primarily focuses on mass and energy balance equations, where pressure and enthalpy serve as primary variables. These variables are solved iteratively using the Newton–Raphson method, enabling precise solutions even in complex reservoir conditions (Voskov, 2017).

To enhance computational efficiency and maintain numerical stability, DARTS incorporates an Operator-Based Linearization (OBL) technique, which simplifies the nonlinear terms in the governing equations (Voskov, 2017). This approach significantly accelerates convergence and improves performance in large-scale simulations (Tomin et al., 2020). Additionally, the simulator can seamlessly handle the presence of multiple fluid phases and varying thermophysical properties of the reservoir media (Voskov et al., 2021). Boundary conditions, including Dirichlet-type constraints, are implemented to simulate interactions with the surrounding environment accurately (Hajibeygi & Karvounis, 2016). The simulator's flexibility allows for dynamic adaptation to changing operational conditions, making it a reliable tool for assessing various heat storage and recovery scenarios in high-temperature aquifer thermal energy storage (HT-ATES) systems (Tomin & Voskov, 2021). DARTS has been extensively validated against benchmark geothermal cases and field data, demonstrating its capability to accurately capture the coupled thermal and hydraulic behavior of subsurface formations (Voskov & Tomin, 2019). It serves as a critical component in optimizing the design and operation of geothermal energy projects, providing insights into long-term system performance and sustainability (Voskov et al., 2021).

3. RESULTS

The performance of the HT-ATES system was evaluated under three different operational scenarios to assess the impact of injection strategies on thermal storage efficiency and heat recovery. The results focus on the evolution of temperature and flow rate profiles, spatial heat distribution, and storage efficiency trends over a 10-year simulation period. The comparison between scenarios highlights the influence of flow rate magnitude and variability on thermal performance, providing insights into the effectiveness of each strategy in maintaining long-term heat retention. This section presents a detailed analysis of these findings.

Figure 4 presents the simulated temperature and flow rate profiles for the hot and warm wells over a 10-year period under three different operational scenarios. In this study, it was assumed that heat could be extracted using both a heat exchanger and a heat pump until the temperature dropped to 20°C during the discharge phase. Consequently, during the heat discharge phase, the temperature of the warm wells stabilizes at 20°C, whereas during the heat charge phase, it is governed by heat conduction dynamics within the reservoir. Similarly, all scenarios assume that the hot wells can be charged up to 90°C. Therefore, during the charge phase, the hot well temperature remains at 90°C, while during the discharge phase or inactive periods (e.g., well shutdowns in Scenario 2), it is influenced by thermal conduction within the reservoir. Figure 4 captures these thermal dynamics across different injection and production strategies. Although the total injected water volume remains constant across all scenarios, variations in flow rates lead to different thermal behaviors, particularly in the early years. In Scenario 2, the reservoir experiences the most significant temperature drop after the first discharge cycle, as higher flow rates result in greater initial thermal depletion. However, as the simulation progresses, the temperature decline following each discharge cycle gradually diminishes, and the reservoir temperature stabilizes around 70°C at the upper level of the hot well screens.

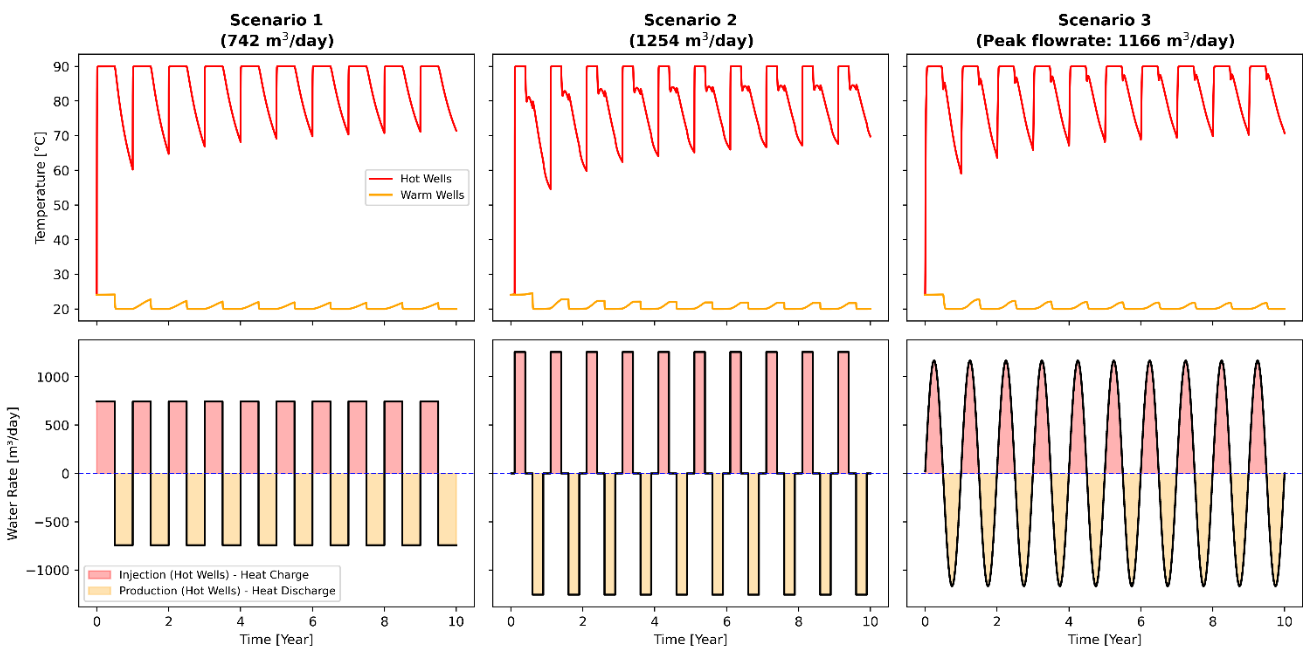

Figure 4: Simulated temperature and flow rate profiles for the hot and warm wells over a 10-year period heat storage under three different operational scenarios.

The spatial distribution of heat within the reservoir is depicted in Figure 5, which presents the temperature maps at the uppermost level of the reservoir after 10 years, following the final discharge period. The thermal plumes indicate that Scenario 2 retains the most extensive high-temperature zone, suggesting improved heat retention due to a higher injection rate. In contrast, Scenario 1 exhibits a slightly smaller heat accumulation region, whereas Scenario 3 results in a more compact thermal distribution, likely due to the influence of the varying injection pattern. The normalized temperature maps further highlight that Scenario 2 maintains a slightly higher temperature compared to the other two cases, although localized variations are observed.

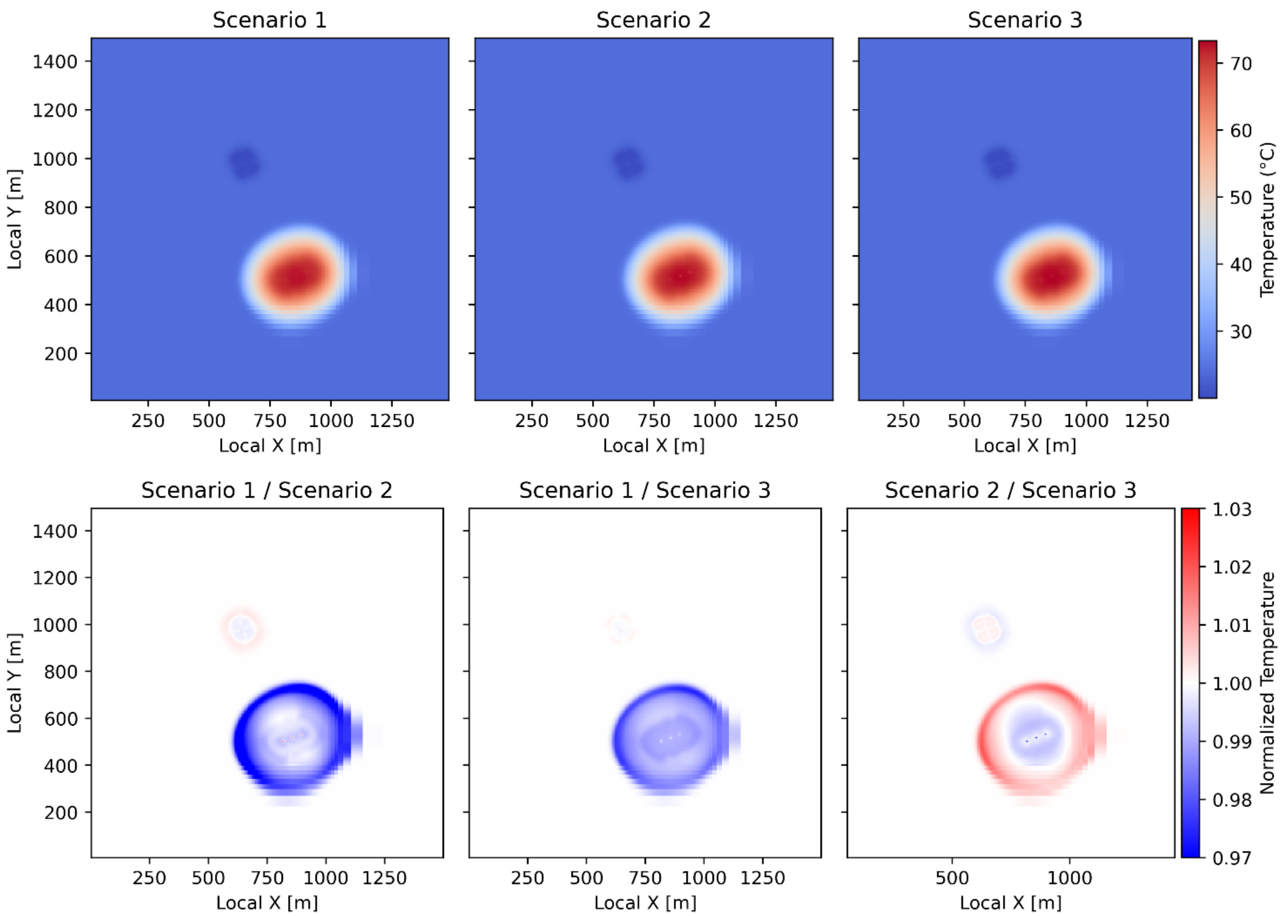

Figure 5 :Temperature distribution at the uppermost level of the reservoir after 10 years, following the final discharge period.

To better understand the vertical extent of heat distribution, Figure 6 presents a cross-sectional view of the reservoir after 10 years. The results indicate that the thermal plume extends both laterally and vertically. In all three scenarios, a similar heat distribution pattern is observed at the end of the simulation, with buoyancy-driven flow causing hot water to accumulate near the upper boundary of the reservoir due to temperature-induced density differences. The thin cap rock layer located immediately above the reservoir prevents further upward fluid migration, limiting heat transfer to the overlying shallow aquifer to purely conductive mechanisms. As a result, thermal energy is largely retained within the near shallow aquifer, with heat diffusion occurring primarily between elevations of -100 m and -130 m without significantly reaching the shallower aquifers. The normalized temperature distributions reveal that Scenario 1 exhibits the lowest vertical temperature retention, while Scenario 2 maintains the highest temperatures within the storage reservoir. In other words, by the end of the 10-year period, Scenario 1 retains the least amount of stored heat within the reservoir, whereas Scenario 2 achieves the highest level of thermal retention.

The evolution of storage efficiency over time for each scenario is illustrated in Figure 7. The results show that Scenario 1 consistently achieves the highest storage efficiency, reaching approximately 63% by the end of the simulation period. Scenario 2 follows a similar trend but remains slightly lower, suggesting that higher injection rates may lead to increased heat losses due to thermal dispersion, while rest periods likely contribute to additional heat loss through conduction. Scenario 3, with sinusoidal flow rates, demonstrates an intermediate efficiency, suggesting that dynamic injection offers a balanced approach between heat recovery and operational flexibility. These findings suggest that a moderate and stable injection rate, as in Scenario 1, yields the most efficient heat storage and recovery, while excessive injection rates (Scenario 2) or variable injection patterns (Scenario 3) introduce operational considerations for sustaining efficiency.

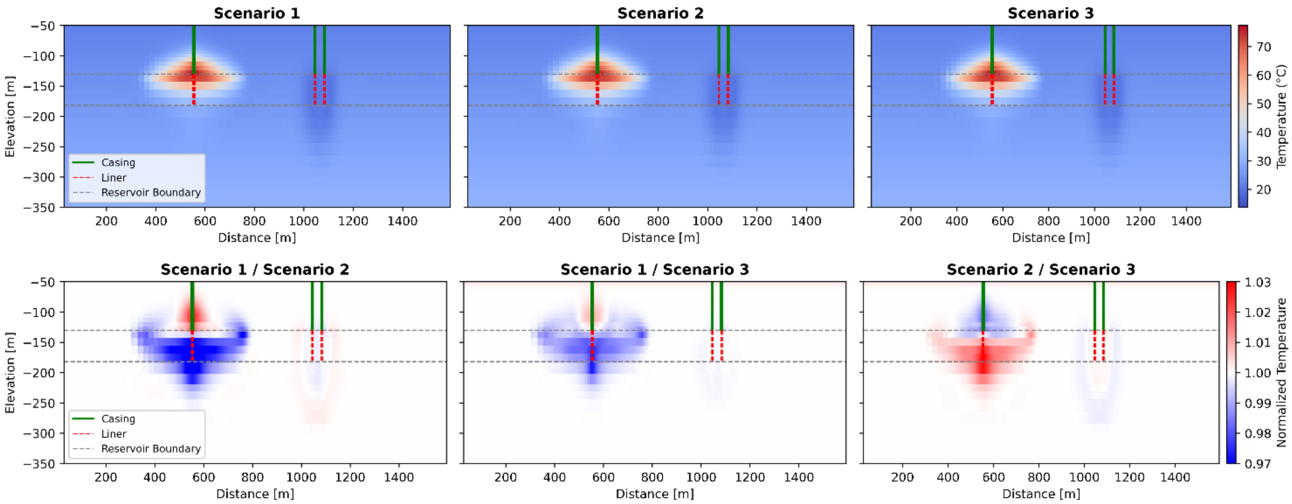

Figure 6 : Cross-sectional view of the reservoir after 10 years, showing the vertical extent of heat distribution. The results reveal buoyancy-driven heat accumulation near the upper boundary of the reservoir and conductive heat transfer to the shallow aquifer. Normalized temperature distributions highlight differences in vertical thermal retention across the scenarios

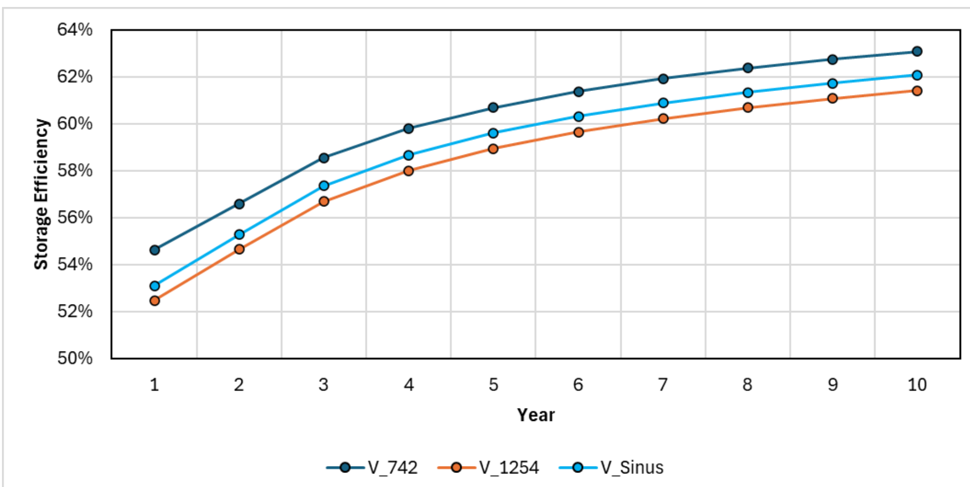

Figure 7 : Evolution of storage efficiency over a 10-year simulation period for each scenario.

4. CONCLUSION AND DISCUSSION

This study explored the thermal performance of a high-temperature aquifer thermal energy storage (HT-ATES) system under different operational strategies, inspired by the subsurface and operational conditions of the TU Delft Campus HT-ATES site, which serves as a pilot demonstration within the PUSH-IT project. The analyses presented here are exploratory in nature and do not aim to precisely represent the actual operational conditions of the system. Instead, they provide insights into the influence of injection strategies on heat storage efficiency and recovery.

The results indicate that injection rate and operational patterns affect thermal retention, heat distribution, and storage efficiency. Among the tested scenarios, a moderate and stable injection rate (Scenario 1) exhibited the highest storage efficiency, minimizing heat losses while maintaining effective heat recovery. In contrast, higher injection rates (Scenario 2) led to increased thermal dispersion, while variable injection patterns (Scenario 3) introduced operational flexibility but required careful management to sustain efficiency. The analysis of temperature distributions showed that buoyancy-driven flow plays a key role in vertical heat migration, with thermal accumulation observed near the upper boundary of the reservoir.

The model results suggest that a thin clay layer above the storage reservoir acts as a cap rock, preventing fluid migration to the overlying aquifer. However, due to its limited thickness, conductive heat transfer occurs, leading to a temperature increase in the adjacent aquifer. Since this aquifer is located between -100 m and -130 m, thermal breakthrough into shallower, near-surface aquifers is not expected.

Moreover, the absence of drinking water resources at Delft further confirms that the heating of the upper layers does not pose a significant concern in this specific case.

It is important to acknowledge that the geological model used in this study is based on the subsurface characterization presented in the feasibility study by Bloemendal et al. (2020), which has since been updated following pilot drilling within the PUSH-IT project. Future analyses will incorporate these revised geological conditions to enhance model accuracy and better reflect the actual subsurface properties. Upcoming simulations will incorporate real heat demand data, enabling the assessment of dynamic heat storage operations under realistic conditions. To improve prediction accuracy, the reservoir model will also be integrated with district heating infrastructure, including heat exchangers and heat pumps, facilitating a holistic evaluation of system-wide interactions. These coupling will support the development of a techno-economic model, assessing the feasibility and cost-effectiveness of HT-ATES deployment under different operational strategies. These advancements will contribute to a more realistic and applicable assessment of HT-ATES performance, supporting its future implementation as a reliable and efficient energy storage solution.

ACKNOWLEDGEMENTS

This study was funded by the European Union under grant agreement 1011096566 (PUSH-IT project). Views and opinions expressed are, however, those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor CINEA can be held responsible for them.

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