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Seasonal High-Temperature Aquifer Thermal Energy Storage in Austria: Preliminary Results of the ATESref Project

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INTRODUCTION

Seasonal Thermal Energy Storage (TES) represents a key technology for sustainable and low-carbon heating systems. By storing surplus thermal energy from renewable and waste sources – such as solar, geothermal, industrial waste heat, and power-to-heat processes – TES enables efficient recovery during periods of high demand, thereby reducing fossil-fuel dependency and supporting climate-mitigation targets (IEA, 2020; Fleuchaus et al., 2018). Among underground TES (UTES) concepts, Aquifer Thermal Energy Storage (ATES) and Borehole TES (BTES) are the most widely implemented, with system selection governed primarily by local geological conditions (Lee, 2013). ATES systems utilize groundwater in aquifers for heat storage and recovery, offering a cost-effective and technically mature solution (Bloemendal et al., 2018). The high-temperature variant (HT-ATES, ≈ 40–90 °C) is particularly suitable for integration with district heating networks, though its performance strongly depends on site-specific geological and hydrogeological parameters as well as on thermal losses to the surrounding strata (Bloemendal and Hartog, 2018). Under favorable conditions, HT-ATES can achieve significant primary energy savings and reduce annual CO_2 emissions by several thousand tons compared to conventional heat supply (Fleuchaus et al., 2018).

Despite extensive international experience, no commercial ATES facility currently exists in Austria. The Fürstenfeld area in the Styrian Basin is considered a promising candidate due to its well-characterized geothermal resources, available deep wells, and an established district heating infrastructure. The ongoing ATESref project investigates the feasibility of seasonal heat storage in deeper aquifers of this region. It reprocesses and reinterprets existing seismic and borehole data to derive key hydrogeological parameters that serve as input for a numerical model of groundwater flow and heat transport. This model provides a basis for optimizing technical design and evaluating economic integration into the local heating network.

A critical technical challenge concerns the reinjection of thermal water. Previous geothermal operations in the area (wells FF1 and FF2, drilled in 1999) suffered from severe injectivity decline, rendering them uneconomical. ATESref directly addresses this issue by applying recent advances in reinjection technologies to mitigate clogging and maintain long-term operational reliability.

By addressing these site-specific challenges, ATESref constitutes an essential step toward the introduction of ATES technology in Austria. The insights gained are expected to facilitate future implementations in similar geological settings (e.g. Graz) and contribute to the national transition toward sustainable, climate-neutral energy systems.

1 METHODS

1.1 Energy System Analysis and Scenario Development

Operational data from 2024 were used to characterize the existing district heating network, including flow and return temperatures, heat generation mix (biomass CHP, boilers), and potential surplus heat sources such as geothermal or industrial waste heat. These data form the baseline for integrating a seasonal storage unit.

Future supply and demand scenarios for 2030 were developed considering network expansion and generation capacity while maintaining similar operating temperatures. Expected summer heat surpluses were used to determine storage size and charging strategy. It is assumed that after several annual cycles, the ATES will reach a quasi-steady thermal state. If surplus heat proves insufficient for economic operation, additional heat sources will be evaluated through sensitivity simulations to ensure techno-economic feasibility.

1.2 Hydrogeological Conceptual Model

A comprehensive geological and petrophysical analysis of ten deep wells in the Fürstenfeld region (including Frutura, Ilz, Loipersdorf, Blumau and Übersbach) was conducted to characterize the Carinthian Gravel aquifer. This Sarmatian-age coarse clastic unit, composed of sandy gravels with interbedded clays and silts, exhibits high permeability and occurs at depths of approximately 560–650 m.

Geophysical well logs indicate laterally continuous gravel layers (1–10 m thick) separated by fine-grained intercalations. The cumulative aquifer thickness reaches about 85 m in the central area, forming the basis for initial modeling. Hydraulic parameters were derived from available pumping tests and, where lacking, inferred from analogous aquifers in Bad Gleichenberg approx. 20 km south-west of the study area.

1.3 Sequence Stratigraphic Interpretation

To map the spatial distribution of potential reservoir units, geophysical borehole and seismic data (2D and 3D reflection profiles) were analyzed. Nineteen seismic sections and multiple borehole datasets provided by RAG Austria AG and Joanneum Research were interpreted using established sequence stratigraphic concepts (Mitchum et al. 1977; Vail et al. 1977; Posamentier et al. 1988; Posamentier & Allen 1999; Catuneanu 2002). This approach enables reconstruction of depositional sequences and identification of coarse clastic intervals suitable for heat storage.

1.4 Numerical Modeling

Collected geological and operational data serve as input for a 3D coupled groundwater flow and heat transport model (FEFLOW; Diersch, 2014). The preliminary model simulates cyclic injection and extraction at ~100 °C and 30 L/s to analyze thermal propagation, recovery efficiency, and pressure evolution. This schematic model provides process understanding and serves as a basis for a refined model incorporating detailed site-specific data.

2 RESULTS

2.1 Integration Concept

An initial integration concept was developed to couple the planned high-temperature ATES with the Fürstenfeld district heating network. In the quasi-steady state, two storage wells (ATES 1 and ATES 2) operate in a seasonal cycle: during summer, the system is charged with surplus heat from multiple renewable and waste sources (biomass CHP, boilers, large-scale heat pumps, power-to-heat systems, and industrial waste heat). In winter, the stored water (~90 °C) is extracted and post-heated – if required – to reach network supply temperatures of ≈ 100 °C using biomass or electric systems. Ongoing techno-economic simulations evaluate the optimal mix of charging and post-heating technologies to maximize efficiency and minimize fossil fuel use (Figure 1).

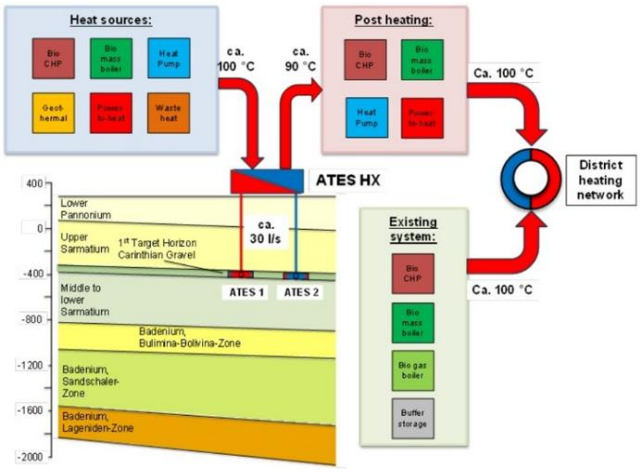


Figure 1. Integration concept for coupling high-temperature ATES with the Fürstenfeld district heating system.

2.2 Hydrogeological Framework

Analysis of borehole data confirmed that the Carinthian Gravel (Sarmatian) forms a laterally continuous aquifer beneath Fürstenfeld between 560 – 650 m depth. The unit comprises alternating gravel and clayey layers totaling ~85 m effective thickness, confined by low-permeability strata above and below.

Hydraulic re-evaluation of legacy wells (FF1, FF2) indicates hydraulic conductivities of 4 – 7 × 10^{-6} m s^{-1} and transmissivities of 1 – 2 × 10^{-4} m^2 s^{-1}, consistent with regional studies (Zojer et al., 2005). These values confirm the aquifer's ability to sustain design flow rates (~30 L s^{-1}). Temperature gradients of 4 – 5 °C / 100 m yield natural formation temperatures of 20 – 25 °C at 500 m depth, favorable for high-temperature storage. Regional groundwater flow is directed SE, which is incorporated into the numerical model to assess thermal plume migration (Figure 2).

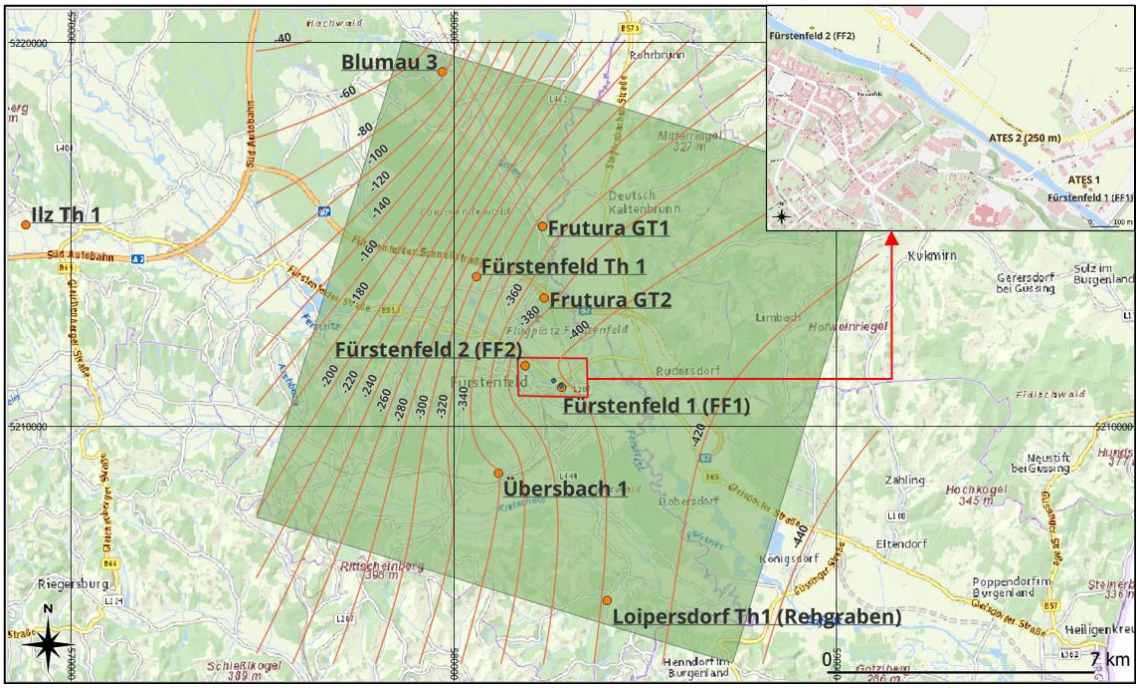


Figure 2. Map of deep boreholes and modeled aquifer extent (Carinthian Gravel).

2.3 Numerical Modeling

A preliminary 3D coupled flow-and-heat-transport model (FEFLOW; Diersch, 2014) was constructed based on the interpreted aquifer geometry and petrophysical parameters (Table 1). The model simulates 25 years of cyclic operation with injection at 100 °C and 30 L s^{-1}. After multiple charge–discharge cycles, aquifer temperatures stabilize around 85 °C with minimal thermal short-circuiting or plume drift.

Table 1. Petrophysical properties of different rock types

Parameter	Unit	Clay marl	Carinthian Gravel
Porosity, n	-	0.03	0.25
Hydraulic conductivity, k	m s^{-1}	1x10^{-8}	2x10^{-5}
Thermal conductivity, λ	W m^{-1} K^{-1}	2.1	2.2
Specific heat capacity, c_p	J m^{-3} K^{-1}	1.8x10^6	2.4x10^6

The surrounding marl and clay units act as effective aquitards, limiting vertical losses. These results indicate that the Fürstenfeld site provides favorable hydraulic and thermal conditions for ATES operation (Figure 3).

2.4 Seismic and Structural Interpretation

Reprocessed seismic data and borehole correlations confirm the lateral continuity of the Carinthian Gravel and reveal only minor faulting within the Sarmatian sequence. The absence of major structural barriers supports stable long-term heat storage. The sequence-stratigraphic interpretation also refines basin architecture and aids calibration of the geological model used for simulation.

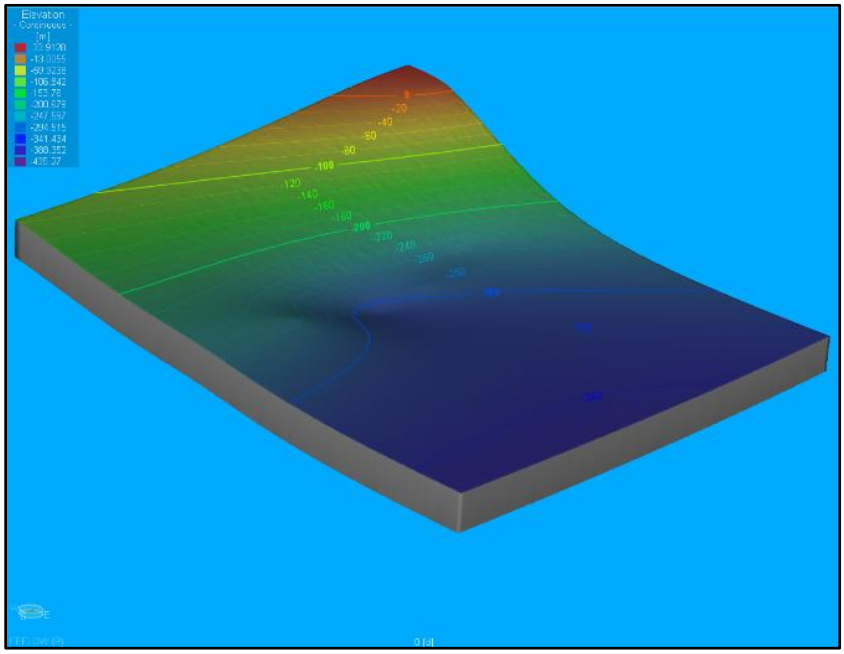


Figure 3. 3D representation of the modeled aquifer used for heat-transport simulations.

3 DISCUSSION

The initial findings of the ATESref project highlight both the strong potential and the main challenges of establishing a high-temperature ATES in the Styrian Basin. The geological framework is favorable: the Carinthian Gravel aquifer is regionally extensive, laterally continuous, and confined by low-permeability strata. Its high transmissivity and good confinement indicate that the required storage volumes can be achieved with limited vertical heat loss. The relatively high geothermal gradient (≈ 4–5 °C / 100 m) further enhances storage efficiency, as the temperature contrast between stored water and host rock remains moderate.

The primary technical challenge concerns reinjection performance. Historical geothermal operations in Fürstenfeld showed that maintaining stable injection in clastic aquifers is sensitive to clogging by fine sediments and chemical precipitates. ATESref therefore focuses on re-evaluating existing wells (FF1, FF2) and testing mitigation measures such as optimized filtration, controlled pressure regimes, and periodic back-flushing. Given the measured hydraulic conductivities (≈ 10^{-5} m s^{-1}), sustainable reinjection at design flow rates (~30 L s^{-1}) appears feasible if clogging can be effectively managed. Lessons from recent HT-ATES projects – such as improved screen design, mild acidizing, or distributed injection – will be incorporated to enhance long-term injectivity (Bloemendal et al., 2018).

Thermal recovery efficiency remains another key parameter. Preliminary simulations indicate that conductive losses to confining layers and limited advective drift will occur, but overall recovery should remain high due to the Styrian Basin's low regional groundwater velocities. Model sensitivity analyses will further explore how aquifer thickness, vertical gradients, and well spacing influence long-term efficiency, supporting the development of optimized operational strategies such as alternating injection/extraction patterns or adjusting seasonal flow direction.

The seismic reinterpretation confirms that the storage horizon is continuous and only slightly faulted, implying minimal hydraulic compartmentalization. This continuity supports future scalability—additional doublets could be installed without significant interference.

From an energy-system perspective, integrating ATES into the Fürstenfeld district heating grid is technically feasible. Available summer heat from biomass CHP, waste heat, and power-to-heat systems appears sufficient to charge the storage. In winter, ATES discharge combined with post-heating (via biomass boilers or heat pumps) could substantially reduce fossil fuel demand. The choice between electric and biomass post-heating will depend on energy prices and emission factors, but in all cases a significant CO_2 reduction is expected through substitution of gas-based heat generation.

4 CONCLUSION

The ATESref project establishes the foundation for Austria's first high-temperature aquifer thermal energy storage system. Preliminary investigations confirm the presence of a suitable deep aquifer near Fürstenfeld,

characterized by adequate thickness, high permeability, and effective confinement—conditions favorable for seasonal heat storage at ≈100 °C. Combined geological and energy-system analyses demonstrate that integrating ATES into the existing district heating grid is technically feasible and could significantly enhance its sustainability by shifting surplus summer heat to winter demand, thereby reducing fossil fuel dependence and CO_2 emissions.

Key challenges remain, particularly the long-term maintenance of well injectivity under cyclic thermal loading. Ongoing work focuses on optimizing reinjection techniques and refining numerical models to ensure reliable operation and to predict thermal and hydraulic behavior with higher confidence.

A techno-economic assessment is in progress to evaluate feasibility under market conditions, including optimal system configuration and regulatory compliance for thermal groundwater use. If successfully implemented, ATESref will serve as a model for deploying seasonal heat storage in comparable sedimentary settings, contributing to Austria's broader decarbonization and renewable heat transition efforts.

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