ATESref - Early Insights and First Results on Aquifer Thermal Energy Storage in Fürstenfeld

Nikolaus Petschacher[1,2], Vilmos Vasvári[1,] Marcellus Schreilechner[3], David Muhr[1], Jakob Huetter[5], Michael Brunneder[4], Moritz Reiser[4], Heinz Binder[3], Christoph Eichkitz[3], Bernd Boechzelt[1] & Franz Hengel[5]

[1]Hydro GmbH, Ludersdorf 69, A-8200 Gleisdorf

[2] Graz University of Technology, Rechbauerstraße 12, 8010 Graz

[3]Geo5 GmbH, Roseggerstraße 17, 8700 Leoben

[4]RED Drilling & Services GmbH, Schwarzmoos, 4851 Gampern

[5]AEE – Institut für Nachhaltige Technologien, Feldgasse 19, 8200 Gleisdorf

petschacher@hydro-gmbh.at

Keywords: Aquifer Thermal Energy Storage, Numerical Modelling, Sequence Stratigraphy, System Integration

ABSTRACT

Aquifer Thermal Energy Storage (ATES) is a promising technology to balance seasonal energy supply and demand by storing excess thermal energy underground during periods of low consumption and retrieving it during peak demand. Although ATES is extensively used in parts of Europe (especially the Netherlands), there are currently no operational ATES systems in Austria. The ATESref project aims to assess the geological, technical, and economic feasibility of implementing seasonal high-temperature heat storage in deep aquifers near Fürstenfeld, Austria. The project includes detailed geological investigations, reprocessing of seismic data, and numerical modeling to identify suitable storage horizons, predict thermal impacts, and tackle the technical challenges of reinjecting heated water into clastic sedimentary aquifers.

Key potential storage horizons have been identified in the Styrian Basin: The Sarmatian-age Carinthian Gravel formation at roughly 650 m depth, and deeper Badenian formations around 1,600 m depth. Using existing well log data and pumping test results, the project evaluates essential hydraulic and thermal properties for the numerical models. These models simulate possible operational scenarios to optimize integration of the ATES into the local district heating network and maximize renewable energy utilization by means of system simulation analysis. Another focus of ATESref is resolving the reinjection issues observed in previous geothermal wells in the region (e.g. Fürstenfeld 1 and 2 drilled in 1999), which had persistent injectivity problems. By leveraging insights from recent reinjection research projects, ATESref seeks to establish reliable reinjection strategies. Successful outcomes of this project would enable dependable long-term ATES operation and encourage wider adoption of ATES technology. Ultimately, ATESref is expected to support the decarbonization of district heating networks, enhance renewable energy integration, reduce reliance on fossil fuels, and contribute to Austria's climate neutrality targets.

1. INTRODUCTION

Seasonal Thermal Energy Storage (TES) is a key technology for sustainable, climate-friendly energy systems. TES allows surplus thermal energy from renewable sources (e.g. solar thermal, geothermal, industrial waste heat, power to heat, waste treatment, etc.) to be stored efficiently and later recovered to meet heating demand. By reducing the need for fossil-fuel backup, TES plays an essential role in decarbonizing the heating sector and achieving climate targets (IEA 2020; Fleuchaus et al 2018; Cabeza et al 2015). Among underground TES (UTES) methods that use subsurface formations for storage, Aquifer Thermal Energy Storage (ATES) and Borehole TES (BTES) are widely implemented around the world, with the choice depending on regional geological conditions (Lee 2013). ATES systems specifically utilize groundwater in aquifers to store and later recover heat, offering a cost-effective, scalable, and technically mature solution (Bloemendal et al 2018). A high-temperature variant, HT-ATES, stores heat at elevated temperatures (≈40 °C to 90 °C) in aquifers. The performance of HT-ATES depends strongly on local geology, hydrogeology, and thermal losses to surrounding strata (Bloemendal and

Hartog 2018). When site conditions are favorable, HT-ATES can yield substantial energy savings and reduce annual CO_2 emissions by thousands of tons compared to conventional heat supply (Fleuchaus et al 2018).

Despite successful ATES deployment in countries like the Netherlands, no commercial ATES facility exists in Austria. The region around Fürstenfeld in the Styrian Basin is a promising candidate for Austria's first ATES system due to known geothermal resources, existing deep wells, and an established district heating network. The ongoing ATESref project is focused on this region, aiming to evaluate the feasibility of seasonal underground heat storage in deeper aquifers near Fürstenfeld. The project builds on extensive prior studies: it reprocesses and reinterprets existing seismic profiles and analyses borehole data to derive essential hydrogeological parameters. These parameters form the basis for robust numerical models that can simulate subsurface fluid flow, heat transport, and storage efficiency. The models also help develop optimal strategies for integrating ATES into the local district heating system, considering technical feasibility and economic viability.

A notable technical challenge in this region is the reinjection of thermal water. Previous geothermal projects near Fürstenfeld (wells FF1 and FF2, drilled 1999) experienced persistent reinjection problems that rendered them uneconomical. ATESref directly addresses this issue: leveraging recent research on reinjection methods, the project aims to overcome clogging and injectivity decline to enable reliable operation. Solving these problems is critical for the success of ATES, as reinjection capacity often limits system performance.

Overall, ATESref is an important step toward introducing ATES in Austria and advancing the country's energy transition goals. The knowledge gained will facilitate broader adoption of ATES technology in similar geological settings (e.g. Graz) and ultimately support Austria's efforts to develop sustainable, climate-neutral energy systems.

2. METHODOLOGY

The project methodology integrates energy system analysis with geological modeling to develop a viable high-temperature ATES concept for Fürstenfeld. Key methodological steps include:

2.1 Energy System Characterization

All relevant data on the existing district heating network and heat supply in Fürstenfeld were collected. This included heating network flow/return temperatures as a function of ambient temperature (using 2024 operational data) and the current heat generation mix (biomass combined heat and power (CHP), boilers, etc.). Any existing surplus heat (e.g. industrial waste heat, geothermal heat, etc.) was identified and quantified. These data form the baseline for integration of a seasonal storage system.

2.2 Scenario Development

Future heating demand and supply scenarios were developed for the year 2030. Projected expansions in the district heating system and generation capacity were considered, assuming that the heating network temperatures remain roughly unchanged by 2030. Potential excess summer heat was estimated from the 2030 generation portfolio to size the storage. It is assumed that after a few years of operation, the ATES will reach a quasi-steady cyclic state such that full storage capacity (at target temperature) is available each winter. If preliminary analysis showed the available surplus heat is too low for an economically viable ATES, additional heat sources would be considered. All in all sensitivity system simulation studies will be carried out to make the ATES economically feasible.

2.3 Hydrogeological Conceptual Model

A detailed geological and petrophysical analysis of existing deep wells was performed to characterize the aquifer suitable for heat storage. Ten deep boreholes in the region were evaluated (including Fürstenfeld, Frutura, Ilz, Loipersdorf, Blumau, and Übersbach wells) to map the extent and properties of the Carinthian Gravel aquifer. The Carinthian Gravel (Sarmatian) is a coarse clastic sequence (sandy gravels with intercalated clays and silts) known for good permeability. It is present across the Fürstenfeld area at roughly 560–650 m below ground level.

Based on geophysical well logs, the gravel layers are laterally extensive; individual gravel beds range from ≈1 m to 10 m thick, separated by marl/silt layers. The base of the Carinthian Gravel was identified in each borehole, allowing an isopach map to be constructed. The total effective aquifer thickness is on the order of 85 m in the central area, when summing the gravel intervals (this composite thickness is used for initial modeling assumptions).

Pumping test data from nearby wells were analysed to estimate hydraulic properties of the aquifer. In absence of a pumping test in Fürstenfeld, results from a multi-well pumping test in Bad Gleichenberg (a similar Sarmatian gravel aquifer a few tens of kilometers away) were considered as an analogy.

2.4 Sequence Stratigraphy

The identification of suitable reservoir rocks for hydrothermal heat storage can be significantly supported by geophysical data. On the one hand, the depth and thickness of coarse clastic sediment horizons can be mapped using geophysical borehole data. On the other hand, 2D and 3D reflection seismic data can be used to determine the spatial distribution of these reservoir rocks.

The spatial distribution of suitable reservoir rocks is directly related to their depositional history with the basin, which is essentially controlled by sea level. Subsequent changes caused by tectonic and erosive events as well as compaction during subsidence alter the properties of these rocks.

Suitable sediments and their distribution can be recognized in the course of a sequence stratigraphic interpretation of the borehole data and the seismic data. This study is based on nineteen seismic sections and data from several boreholes. Seismic sections are displayed in two-way travel time (TWT), where 0 ms TWT corresponds to 200 m above sea level. Nine seismic sections and information on deep wells Übersbach 1, were kindly provided by RAG Austria AG (Vienna). Ten additional seismic lines were acquired and processed during the last twenty years by Joanneum Research during exploration for drinking and geothermal water resources.

The sequence stratigraphic concept is based on the methodology and terminology of Mitchum et al (1977 a,b); Vail et al (1977a,b); Posamentier et al (1988); Posamentier and Allen (1999) and Cantuneanu (2002).

2.5 Numerical Modeling

The collected data feed into ongoing numerical simulations of heat storage performance. A first schematic 3D coupled flow and heat transport model of the aquifer and surrounding formations is being developed (using FEFLOW; Diersch 2014). The model simulates cyclic injection and extraction of water (at≈100 °C injection and 30 l/s) to evaluate thermal propagation, energy recovery efficiency- and pressure behavior. The first schematic model primarily serves to provide an understanding of the processes involved in ATES systems. Subsequently, a detailed model will be developed based on geophysical and petrophysical data.

3. FIRST RESULTS

3.1 Integration Concept Design

An initial heat source and sink portfolio was created for integrating the ATES into the local energy system. This portfolio includes a diversified set of heat sources to charge the ATES in summer, and post-heating systems to utilize the stored heat in winter. Figure 1 illustrates the system integration concept after quasi-steady cycle state conditions, where the ATES (two high-temperature storage wells, ATES 1 and ATES 2) is charged in summer by various sources and discharged in winter to feed the district heating network. Identified heat sources include:

- Biomass-fired combined heat and power (Bio CHP),
- Biomass boilers,
- Large-scale heat pumps,
- Power-to-heat systems (using excess PV electricity),
- Industrial or other waste heat streams,
- (Possibly geothermal heat, though not considered in the initial concept).

On the heat sink side, the stored hot water (around 90 °C) is extracted in winter and boosted if necessary, by post-heating systems to meet the network supply temperature (≈100 °C). The following post-heating technologies were evaluated:

- Biomass CHP and biomass boilers (existing units),
- Electric heat pumps (which can both raise output temperature and cool the return water, increasing ATES discharge efficiency),
- Power-to-heat (electric boilers or resistive heaters),
- (A supplemental geothermal plant could also be an option in the future).

Ultimately, a techno-economic analysis (ongoing) will compare these integration options in operational scenarios to identify the optimal system. Figure 1 shows the conceptual design with the ATES as a core component of the district heating network.

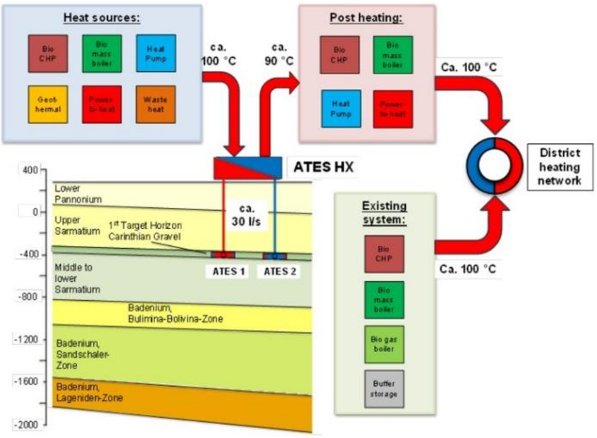

Figure 1: Concept for integrating a high-temperature ATES into the Fürstenfeld district heating system. Heat sources (left) charge the aquifer storage in summer (≈100 °C injection), and post-heating systems (right) reheat output in winter as needed to supply ≈100 °C to the network.

The goal is to identify the most cost-effective mix of sources and post-heating such that the ATES can operate efficiently and reduce fossil fuel usage in winter.

3.2 Hydrogeological Conceptual Model

The analysis of borehole data confirmed that the Carinthian Gravel aquifer is present and laterally extensive beneath Fürstenfeld at the targeted depth

(≈560–650 m below ground). The aquifer consists of multiple sandy gravel layers totaling ≈85 m thickness, with intervening clayey layers. It lies above Badenian claystone formations and below Pannonian sands (which are thinner in this area). Table 1 summarizes key data from the boreholes used in the model, including ground elevation, total depth, and depth of the Carinthian Gravel base.

Table 1: Key data from deep wells in the study area, used to delineate the target aquifer (Carinthian Gravel, Sarmatian). Negative elevations indicate depth below sea level.

Borehole	Ground level [m a.s.l.]	Total depth [m]	Bottom Carinthian gravel [m a.s.l.]
Fürstenfeld 1	251	1950	-399.0
Fürstenfeld 2	252	1800	-398.0
Fürstenfeld Th 1	263.73	3145	-301.3
Frutura GT1 Frutura GT1a	257	3256.5 3000	-348
Frutura GT2	259.44	3188	-370.6
Ilz Th 1	292	1906	-70
Loipersdorf Th1 (Rehgraben)	252,8	1140	-402.2
Blumau 3	271	1200	-76
Übersbach 1	270.7	2692	-339,3

Figure 2 shows the location of the key wells and the modeled aquifer extent. The base of the Carinthian Gravel slopes gently across the area and is deepest towards the east (around -400 m a.s.l.). The overlying and underlying clay-rich strata form an effective aquifer confinement, meaning the hot water will remain contained vertically – a crucial factor for high-temperature storage.

Hydraulic testing results indicate that the aquifer has high hydraulic conductivity on the order of 10^{-5} to 10^{-6} m/s. Re-evaluation of the historical pumping tests in the Fürstenfeld geothermal wells yields an estimated vertical hydraulic conductivity $K \approx 4–7\times10^{-6}$ m/s in the Carinthian Gravel, with corresponding transmissivity ≈1 to 2×10^{-4} m²/s (for ≈85 m thickness). For example, well FF1 is inferred to have $K \approx 7.10\times10^{-6}$ m/s (transmissivity $\approx1.92\times10^{-4}$ m²/s), and FF2 about 4.15×10^{-6} m/s (transmissivity $\approx1.12\times10^{-4}$ m²/s). These results are of the same order of magnitude as previous regional studies (Zojer et al 2005) and confirm that the aquifer can sustain the flow rates required for ATES. The injectivity of the wells – a critical parameter for ATES – is still under evaluation, but initial indications are that, in clean conditions, the wells should accept the design injection flow (around 30 l/s) at moderate overpressure.

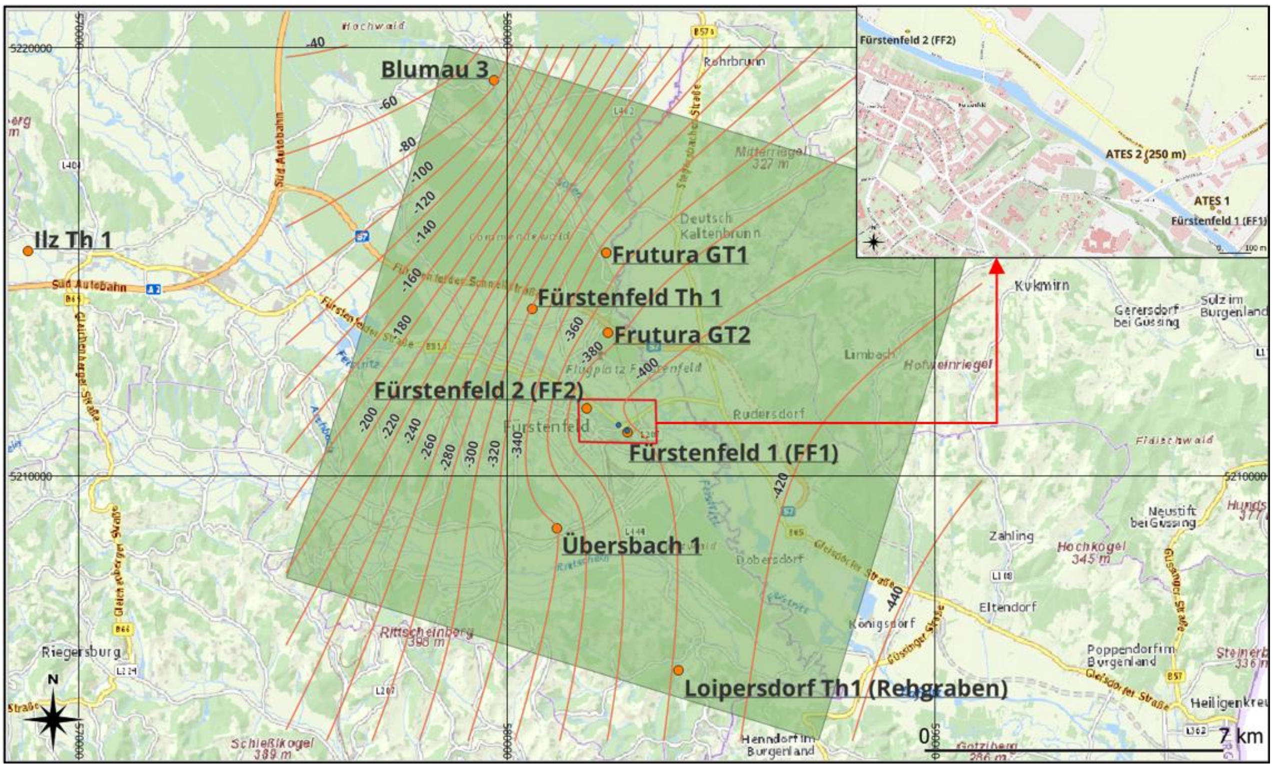

Figure 2: Map of the study area near Fürstenfeld, showing deep borehole locations and the model area (green shaded area). Red contour lines (in m a.s.l.) indicate the interpreted elevation of the base of the aquifer.

However, the historical reinjection problems in this area highlight that maintaining injectivity over time can be challenging. The 1999 geothermal tests experienced rapid decline in well acceptance due to clogging by fine sediments. As part of ATESref, these issues are being revisited: water chemistry is being analysed and filtration/reinjection strategies (e.g. periodic backwashing, maintaining positive pressure to prevent gas exsolution) are being planned. A positive finding is that the target aquifer's permeability, as measured, is relatively high, so if clogging can be managed, the aquifer is capable of high throughputs.

Temperature data from the deep wells provide insight into the geothermal regime. In the Fürstenfeld area, the geothermal gradient is relatively high, around 4 to 5 °C/100 m near surface, decreasing somewhat with depth. This yields aquifer temperatures of ≈20 to 25 °C at 500 m depth and ≈40 °C at ≈1000 m (formation static temperatures). Such gradients are consistent with the fact that the region lies on the western margin of the Pannonian Basin, where the Earth's crust is thinner and the mantle is uplifted, leading to higher heat flow (Elster et al 2016). The higher natural temperatures are favorable for ATES, as they reduce the relative heat loss to the surrounding formation when storing water at ≈100 °C (the thermal gradient between stored water and rock is smaller). The regional groundwater flow in the target aquifer is inferred to be directed toward the southeast (from the Alps towards the basin interior). Shallower confined aquifers in the area exhibit a similar flow direction (Zojer et al 2005). This means that there will be a natural hydraulic gradient across the ATES site. The modeling studies include this effect to ensure the thermal plume migration remains within acceptable bounds.

3.3 Numerical Modeling

The geometry of the model aquifer is defined from the conceptual model. Figure 3 shows a preliminary 3D representation of the Carinthian Gravel aquifer volume used in simulations. The model considers the overlying and underlying strata (thick marl/clay layers) which have very low hydraulic conductivity and act as aquitards, limiting vertical heat loss. Boundary conditions incorporate regional groundwater flow and heat flux. The model will be used to examine different well configurations and operational strategies (e.g. continuous vs. batch-wise injection) to optimize the storage efficiency and minimize thermal losses.

The petrophysical properties of the rock types were set according to the values in Table 2. For the groundwater were assumed: $\lambda_w = 0.62$ W·m^{-1}·K^{-1} and $c_w = 4.18 \times 10^6$ J·m^{-3}·K^{-1}.

The energy to be fed in is to be supplied from the heat sources with a temperature of 100 °C via a heat exchanger. The geothermal well ATES 2 can provide a flow rate of 30 l/s. The heat is fed into well ATES 1 and the water required for this is taken from well ATES 2 (Figure 1). The loading phases take place from mid-May to mid-September, the discharging phases from mid-November to mid-March, and the holding phases from mid-March to mid-May and mid-September to mid-November, respectively. The simulation was carried out over a period of 25 years starting on 1st January. The temperatures simulated in the wells ATES 1 and 2 are shown in Figure 4. After 25 years of operation of the doublet, a temperature of 85°C is to be expected in the aquifer reservoir.

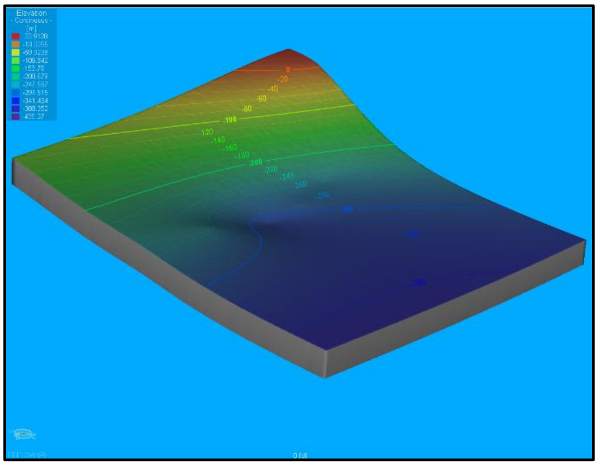

Figure 3: 3D view of the modeled aquifer (Carinthian Gravel) in the Fürstenfeld area, with vertical exaggeration 10×. The sloping surface represents the bottom of the aquifer.

Table 2: Petrophysical properties of different rock types.

Parameter	Unit	Clay marl	Charintian 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

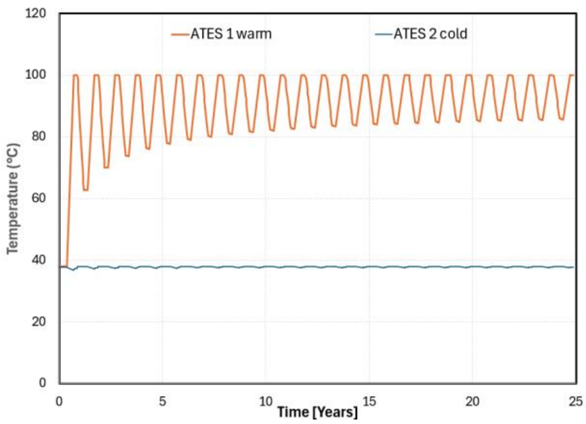

Figure 4: Simulated temperature in well ATES 1 and 2.

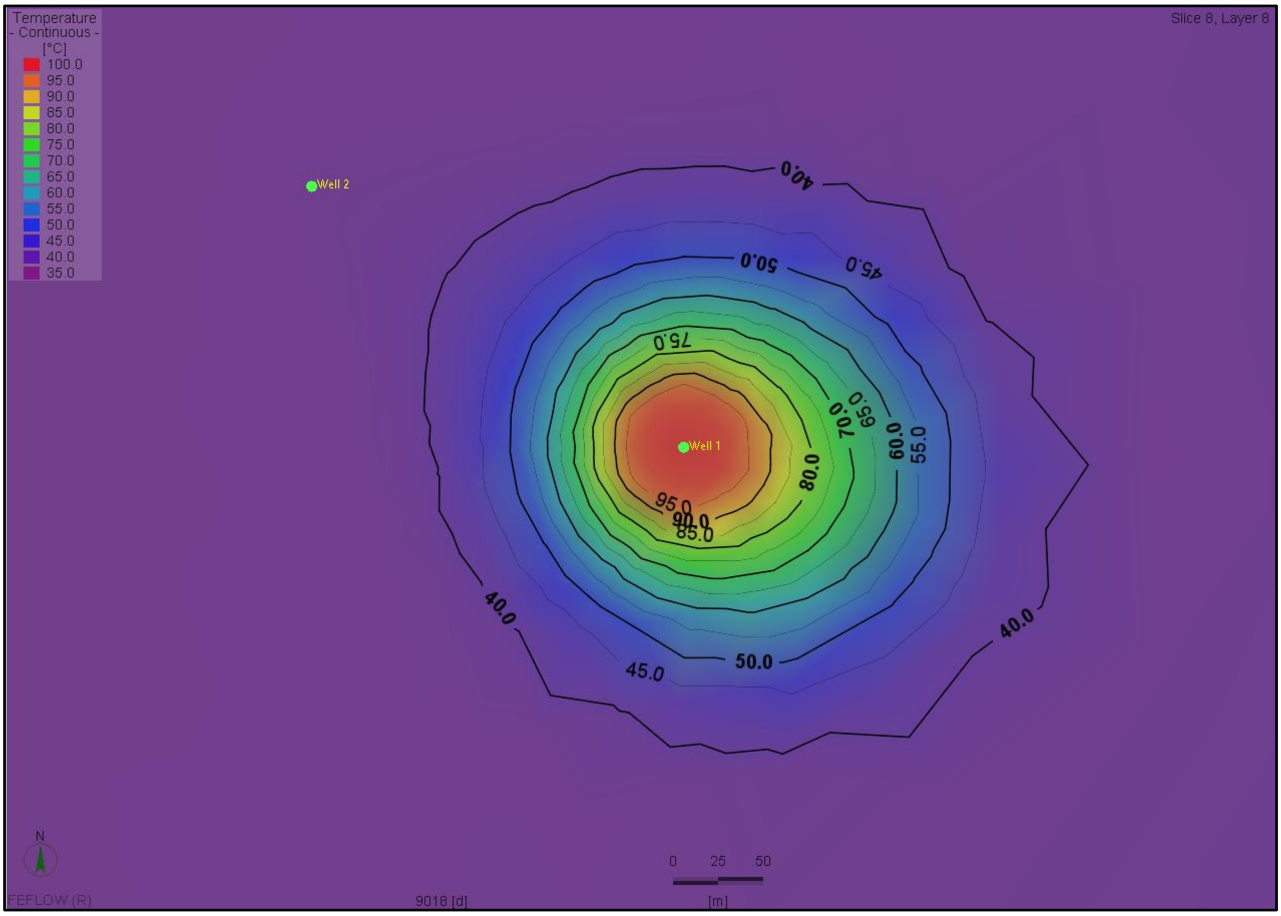

Figure 5: Temperature distribution in the middle of the aquifer after 25 loading phases.

Accordingly, there is no risk to the system from a thermal short circuit after 25 years of operation. Due to the natural groundwater flow (hydraulic gradient 3‰, NWW-SEE directed), only minimal transport of the heat plume in the flow direction can be observed (Figure 5). The greatest hydraulic effect after a loading phase is shown in Figure 6, while that after an unloading phase is shown in Figure 7. The hydraulic range of the alternating extraction and reinjection operation of the doublet is approx. 1.5 km around the wells. Neighbouring wells are not affected by the operation of the doublet.

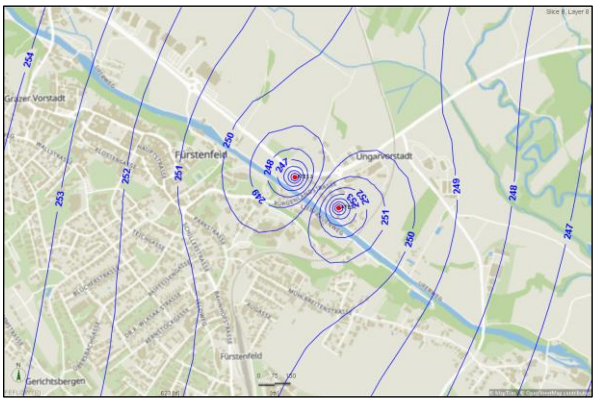

Figure 6: Hydraulic head distribution after a loading phase in well ATES 1.

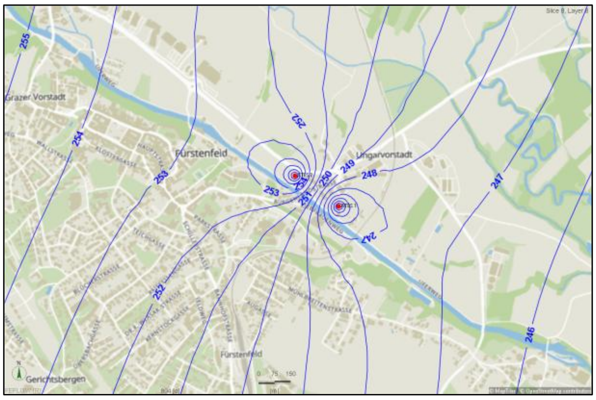

Figure 7: Hydraulic head distribution after a discharge phase in well ATES 1.

3.4 Seismic Interpretation and Reservoir Structure

Reprocessed seismic data and seismo-stratigraphic interpretation together with data form well logs have improved the understanding of the subsurface structure. A key outcome is a refined seismo-stratigraphic interpretation of the basin's layering and faulting, which helps confirm the continuity of the Carinthian Gravel and identify any major faults that could affect the ATES. Figure 8 shows an example of an interpreted seismic section (NW–SE oriented) through the project area. The upper part of the section (Sarmatian/Pannonian) reveals sub-horizontal reflectors corresponding to alternating gravel and marl layers. The Carinthian Gravel unit is part of this Sarmatian sequence and is relatively flat-lying near Fürstenfeld, bounded below by a clear reflector (top Badenian). Several normal faults are visible, but they appear to have limited offset in the Sarmatian layers and likely do not compartmentalize the aquifer significantly. Major stratigraphic markers (labeled "SAR-1.1" to "SAR-1.5" for Sarmatian horizons, and "PAN-1.x" for Pannonian) have been correlated across the area. The Fürstenfeld Th1 well (FF Th1) is marked on the section; it penetrated the Sarmatian sequence and into the Badenian. The seismic interpretation confirms that the storage horizon is continuous and not cut by large faults at the site, which is favorable for ATES operation (no major barriers to flow or sudden changes in thickness). Minor faults may enhance vertical communication or cause slight heterogeneity, but those are being accounted for in the geological model.

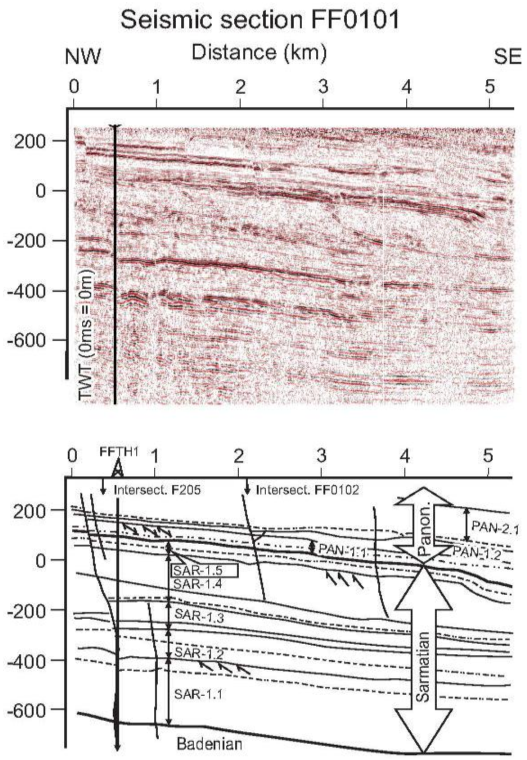

Figure 8: Interpreted NW–SE seismic section through the Fürstenfeld area (seismic line FF0101). Top: processed seismic reflection image (time section). Bottom: seismostratigraphic interpretation highlighting Sarmatian gravel-marl sequences (SAR-1.1 to SAR-1.5) and the overlying Pannonian (PAN) layers. The bold black vertical line marks the approximate position of well FF Th1. The Carinthian Gravel aquifer corresponds mainly to the Sarmatian interval between SAR-1.2 and SAR-1.4. This interpretation supports the lateral continuity of the aquifer (Schreilechner and Sachsenhofer 2007).

4. DISCUSSION AND OUTLOOK

The initial results of the ATESref project demonstrate both the potential and the challenges of implementing a high-temperature ATES in the Styrian Basin. On the positive side, the geological setting appears favorable: there is a regionally extensive aquifer at manageable depth with high permeability and good confinement. The Carinthian Gravel should be able to store the required volumes of hot water, and the overlying clays will minimize upward heat loss. The presence of multiple wells with consistent stratigraphy has reduced uncertainty in the aquifer geometry. Furthermore, the natural thermal regime is advantageous – the relatively high geothermal gradient means that ambient temperatures at depth are higher than in other regions, improving the efficiency of storage (less heat will dissipate to the cooler surrounding rock).

A critical challenge remains the reinjection capability. The historical data from Fürstenfeld's earlier geothermal wells highlight that sustaining injection at 30 l/s or less into a clastic aquifer requires overcoming clogging issues. The fine content in the gravel and potential chemical reactions can significantly reduce permeability near the well. The ATESREF project addresses this issue by re-evaluating existing pumping and reinjection tests and performing a technical assessment of the existing wells FF1 and FF2, primarily aimed at minimizing external and internal fine particles. If this succeeds, the measured high hydraulic conductivity ($\approx 10^{-5}$ m/s) suggests that the aquifer can accommodate the flow rates with only moderate pressure build-up. The project will also draw on lessons from recent reinjection research in analogous systems – for example, optimizations of well screen design, acidizing treatments, or dispersed injection via multiple wells to spread out the thermal and hydraulic load (Bloemendal et al 2018). Successfully demonstrating stable reinjection over multiple cycles would be a significant breakthrough for geothermal energy storage in this region.

Another point of discussion is the thermal recovery efficiency. Numerical simulations (ongoing) will help quantify how much of the injected heat can be extracted after a given storage period. Early indications (and experience from HT-ATES in other sites) suggest that losses will occur due to heat conduction into the confining layers and some advective loss if groundwater flow carries heat downgradient. The Styrian Basin's relatively low regional flow velocity is beneficial here – the hot plume is not expected to drift far between seasons. The 3D model will allow to test different operational strategies (for instance, alternating injection wells every season to create a thermal barrier, or injecting slightly into the natural flow direction to push the hot plume upstream). Sensitivity analysis will identify the key factors influencing efficiency, such as the thickness of aquitards, background vertical thermal gradient, and well separation. These results will guide design adjustments, like adding insulation in the well or modifying injection/extraction schedules.

The seismic re-interpretation has provided reassurance that no major faults disrupt the aquifer continuity at the planned site. Small-scale heterogeneities will be incorporated into the model as needed, but overall the aquifer behaves as a single connected reservoir. This continuity is important for scalability – it means multiple injection/extraction well doublets could be deployed in the future without running out of storage space or interfering with each other too strongly.

From an energy system perspective, integrating ATES into Fürstenfeld's district heating grid appears technically feasible. The concept analysis shows that there are enough renewable/excess heat sources in summer to charge the storage. In winter, using ATES could significantly reduce gas boiler operation, with biomass and heat pumps as post heater covering any temperature boosting required. One consideration is that operating a large heat pump to upgrade ATES output to 100 °C will consume electricity – the trade-off between using direct electric heating versus using the heat pump (with a coefficient of performance taking heat from the ATES) will depend on electricity pricing and emission factors. On the other hand, biomass boilers use biomass as fuel and depends also on the market prices. However, these economic aspects will be evaluated in the next phase of the project. Nevertheless, even with some electrical or biomass as fuel input, the overall CO_2 reduction by displacing fossil fuel combustion is expected to be substantial.

5. CONCLUSION

The ATESref project has laid the groundwork for what could become Austria's first high-temperature aquifer thermal energy storage system. Initial findings confirm the presence of a suitable deep aquifer near Fürstenfeld, with sufficient thickness, permeability, and confinement to allow seasonal heat storage at temperatures around 100 °C. The combination of geological characterization and energy system modeling carried out so far indicates that integrating ATES into the existing district heating network is not only feasible but could markedly improve the sustainability of the heat supply. By storing summer surplus heat (from biomass CHP, industrial waste, etc.) and returning it in winter, the system would reduce reliance on natural gas and help Austria meet its climate neutrality targets.

Several challenges and next steps have been identified. Foremost, maintaining injectivity during repeated thermal cycling will be critical. The project will continue to refine reinjection techniques, informed by a re-evaluating of existing pumping and reinjection tests and numerical simulation, to ensure long-term operational stability of the storage wells. Additionally, the numerical models will be validated and calibrated with any new data to improve confidence in temperature predictions and to optimize the storage management.

Finally, a detailed techno-economic assessment is underway to evaluate the project's viability under real market conditions. This includes optimizing the mix of charging and discharging technologies and ensuring compliance with all regulatory aspects (such as thermal groundwater use permits in Austria). If successful, the ATESref project will provide a blueprint for scaling up ATES in similar sedimentary basins, not only in Austria but also in other regions seeking to balance seasonal energy supply. The outcome will support broader adoption of ATES technology, thereby advancing the decarbonization of heating networks and increasing the share of renewable energy in the heating sector.

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Acknowledgments: The authors thank all project partners and funding agencies for their support. We also thank our colleagues at RAG Austria AG for providing historical borehole data and seismic profiles. (This project is supported by the Austrian Climate and Energy Fund under the 2024 Energy Research Programme of the Austrian Research Promotion Agency.)