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A Framework of Dynamic Surface–Subsurface Co-Simulation for HT-ATES Integration in Large-Scale Heating Networks

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ABSTRACT

Modelling the integration of High-Temperature Aquifer Thermal Energy Storage (HT-ATES) into geothermal-based heating networks is essential for understanding how such systems can enhance operational performance and reduce reliance on fossil-fuel backup. Seasonal storage enables surplus geothermal energy to be stored during low-demand periods and utilised during peak heating seasons, improving the flexibility of large networks where multiple components interact under variable thermal and hydraulic conditions. Coordinating these interactions remains challenging because system inertia, hourly demand variations, return-temperature dynamics, and operational uncertainties affect behaviour of components both at surface and subsurface systems. This study applies a dynamic co-simulation framework that couples a detailed surface system modelled in TESPy and subsurface HT-ATES system modelled in open-DARTS to analyse a full-scale heating system in Delft, the Netherlands, where a geothermal doublet, an HT-ATES system, a stratified buffer tank, a heat pump and a natural gas boiler supply heat to the university campus and the district heating network. The operational strategy utilizes demand-driven flow rate based control combined with dynamic availability checks, specifically accounting for return temperature variations caused by the evaporator bypass. The co-simulation framework enables capturing these variations consistently by how short and long term dynamics interact over multi-year operation. By evaluating thermal performance, energy flows, and operational behaviour over multiple years at both the storage and network levels, the approach provides insights into how HT-ATES can support resilient geothermal-based heating systems while maintaining flexibility and reducing dependence on fossil-fuel backup. Results show that HT-ATES discharge increases by nearly 50%, while boiler use decreases from 13.4 GWh to 7.8 GWh by nearly 41%, over five years of operation.

1 INTRODUCTION

Underground thermal energy storage plays an important role in balancing seasonal variations between geothermal heat production and district heating demand. Seasonal storage has been shown to support system flexibility at district scale (Lyden et al., 2022; Stemmle et al., 2024), and ATES has a long operational history in the Netherlands, where favourable conditions have enabled widespread adoption (Bloemendal et al., 2023; Fleuchaus et al., 2018). Extending this concept to higher temperatures allows HT-ATES to interact directly with geothermal systems and contribute to large-scale heating networks. In such settings, flow-rate constraints, return-temperature variations, and operational decisions strongly influence both surface performance and the long-term operation of the subsurface (Daniilidis et al., 2022).

Although the basic working principle of such systems is relatively straight forward, operating them accordingly is challenging. System inertia, hourly demand variations, return-temperature dynamics, and operational uncertainties affect behaviour of components both at surface and subsurface. Therefore, dynamic modelling is needed to represent these coupled processes, since simplified or steady-state approaches cannot account for hourly fluctuations in heat demand, temperature-driven operational decisions, or the long-term thermal development of the aquifer. While subsurface models are incorporated via analytical or data driven models (Geerts et al., 2025a; Geerts et al. 2025b), recent reviews indicate growing interest in co-simulation methods for combining geothermal and surface energy system models, but also note that only a limited number of studies incorporate detailed subsurface simulators within such frameworks (Yazdani et al., 2026).

This study applies a dynamic co-simulation approach to the geothermal demonstration site in Delft within the PUSH-IT project (Vardon et al., 2024a; Vardon et al., 2024b; Bloemendal et al., 2020). The system includes a deep geothermal doublet, an HT-ATES system, a stratified buffer tank, a heat pump and boiler supplying heat to

both the Delft University of Technology campus (TUD) and the Delft district heating network (OWD). The approach also incorporates demand driven flow-rate-based control with dynamic charge and discharge availability checks, allowing the co-simulation to represent operational decisions that depend on both surface constraints and subsurface conditions. The analysis focuses on how flow-rate-based operation, storage availability, and return-temperature dynamics influence long-term system behaviour at both the surface and subsurface storage and network levels. The work contributes to ongoing efforts to improve the operational integration of HT-ATES and to better understand how system dynamics, component sizing, and temperature set-points influence overall performance. The framework also provides a basis for testing the robustness of future geothermal-based heating networks under different demand and operational scenarios.

2 SYSTEM DESCRIPTION

The heating infrastructure in Delft consists of a multi-source energy system that supplies heat to the Delft University of Technology campus (TUD) and the city district heating network (OWD), as shown in Figure 1. The system is built around a deep geothermal doublet that operates continuously and provides the main renewable heat supply (Voskov et al., 2024a).

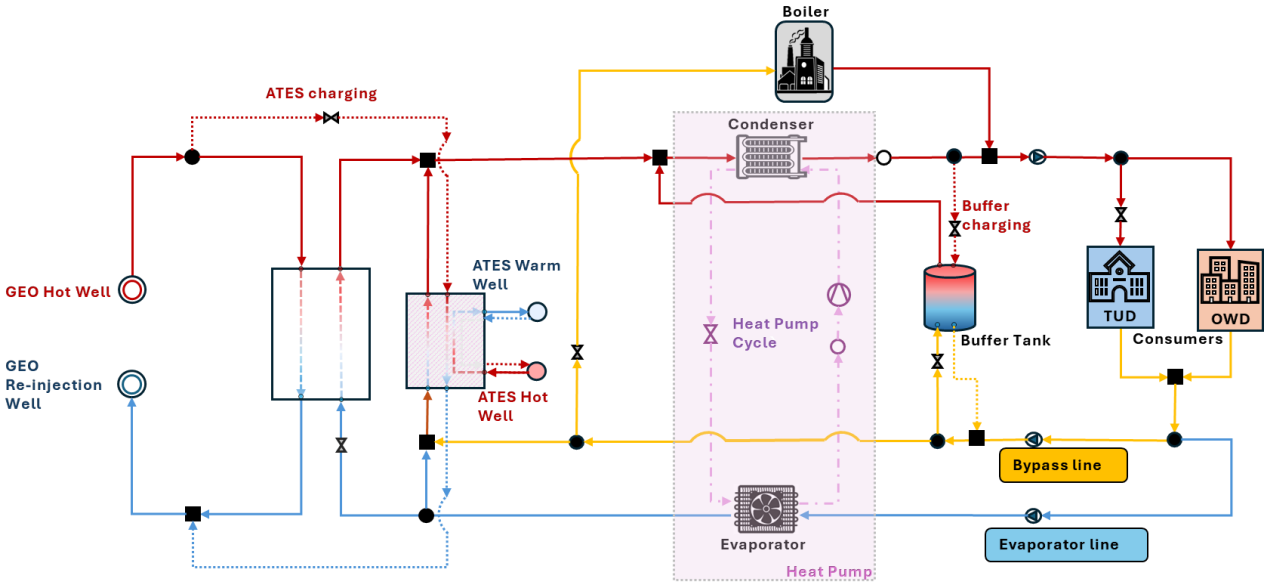


Figure 1. Schematic configuration of the heating infrastructure of Delft demo site.

Two storage components, an HT-ATES unit and a stratified buffer tank, are integrated to cover both seasonal and short-term demand shifts. The HT-ATES system uses a hot well to store surplus heat and a warm well to inject cooled water during discharge. Its ability to charge or discharge depends on the temperature levels in the wells and on the mixed return flow from the evaporator and bypass lines at the surface system. The buffer tank adds further flexibility by storing or releasing heat on shorter timescales.

A heat pump raises the temperature of the combined flow from the geothermal doublet, the HT-ATES system, and the buffer tank to the supply temperature required by the networks. When the return flow from the networks exceeds the evaporator capacity, part of it is diverted through a bypass line, resulting in a mixed return temperature downstream. When the return flow passes through the evaporator, this cooling step lowers the temperature that returns to the surface system, which increases the temperature difference between the hot well and the incoming return flow. As a result, the ATES can continue discharging at lower operational cut-off temperatures, improving the usability of the stored heat under varying network conditions.

A natural-gas boiler provides additional heat only when the combined output from the geothermal doublet, HT-ATES, and the buffer tank is insufficient to meet the instantaneous demand. The overall operational strategy prioritises geothermal source and storage components before resorting to boiler use. Consequently, return temperatures from the TUD and OWD networks, along with flow-rate constraints such as the evaporator limit, play an important role in determining which components operate at each moment.

3 CO-SIMULATION FRAMEWORK

The co-simulation framework couples the surface energy system model with a subsurface model of the HT-ATES wells. Information is exchanged at every hourly step, so that operational decisions made in the surface system

determine the flow and temperature conditions applied at the wells. In the following step, the updated well temperatures in the reservoir model are passed back to the surface model and influence the next operational decision. A stratified buffer tank model is also included in the surface domain to represent short-term storage.

3.1 Surface Model

The surface model is implemented in TESPy (Witte and Tuschy, 2020) and includes all surface energy infrastructure. This covers the geothermal doublet, the evaporator and condenser branches of the heat pump, the boiler, the buffer tank interfaces, and the network supply and return connections. TESPy computes temperatures, enthalpies, flow rates, and energy balances for all components and provides the operational state of the surface system at each hourly step.

3.2 Subsurface Model

The HT-ATES subsystem is simulated using open-DARTS (Voskov et al., 2024b), an open-source reservoir simulator for coupled heat and fluid transport in porous media. The model represents the hot and warm wells located in the Maassluis Formation, which forms the main storage aquifer at the Delft site (Akin et al., 2025). A refined grid is used around the wells to capture temperature and flow variations, with coarser spacing applied farther from the storage region. At each time step, the surface model supplies the injection and production flow rates together with the injection temperature. open-DARTS then computes the resulting temperature distribution in the HT-ATES reservoir. The temperatures at the well screens are passed back to the surface model and used directly as boundary conditions for the next step in the co-simulation loop.

3.3 Buffer Tank Model

The stratified buffer tank is included in the surface domain to represent short-term thermal storage. The model tracks the vertical temperature distribution inside the tank and updates its state of charge based on the net surplus or deficit in the surface system. The numerical formulation is adapted from Tol (2025). The model uses a finite-volume Crank–Nicolson scheme to solve the one-dimensional energy balance and has been integrated directly into the co-simulation loop for this study.

During charging, incoming flow mixes with the appropriate layer and the temperature profile is updated while preserving stratification. During discharging, heat is withdrawn from the upper layers. The resulting outlet temperature and the updated state of charge are passed back to the TESPy model in the next step, where they influence the flow-rate-based operational decisions.

3.4 Forward-Run Approach and Co-Simulation Workflow

Dynamic operation of the Delft system requires assessing, at each hour, whether charging or discharging is feasible. To manage this, the controller in the surface model uses a forward-run approach (Figure 2). At each time step, short feasibility checks are performed to determine whether charging or discharging is possible based on the mixed return temperature from the heating networks, the current hot well temperatures, and the state of charge of the buffer tank. If a given mode is not feasible, the controller proceeds to the next option in the flow-rate-based hierarchy.

Once a feasible option is identified, the surface model calculates the corresponding injection or production flow rates and sends them, together with the injection temperature, to the subsurface model. open-DARTS then computes the resulting well temperatures for the hot and warm wells. These temperatures are returned to the surface model and used as boundary conditions for the next time step.

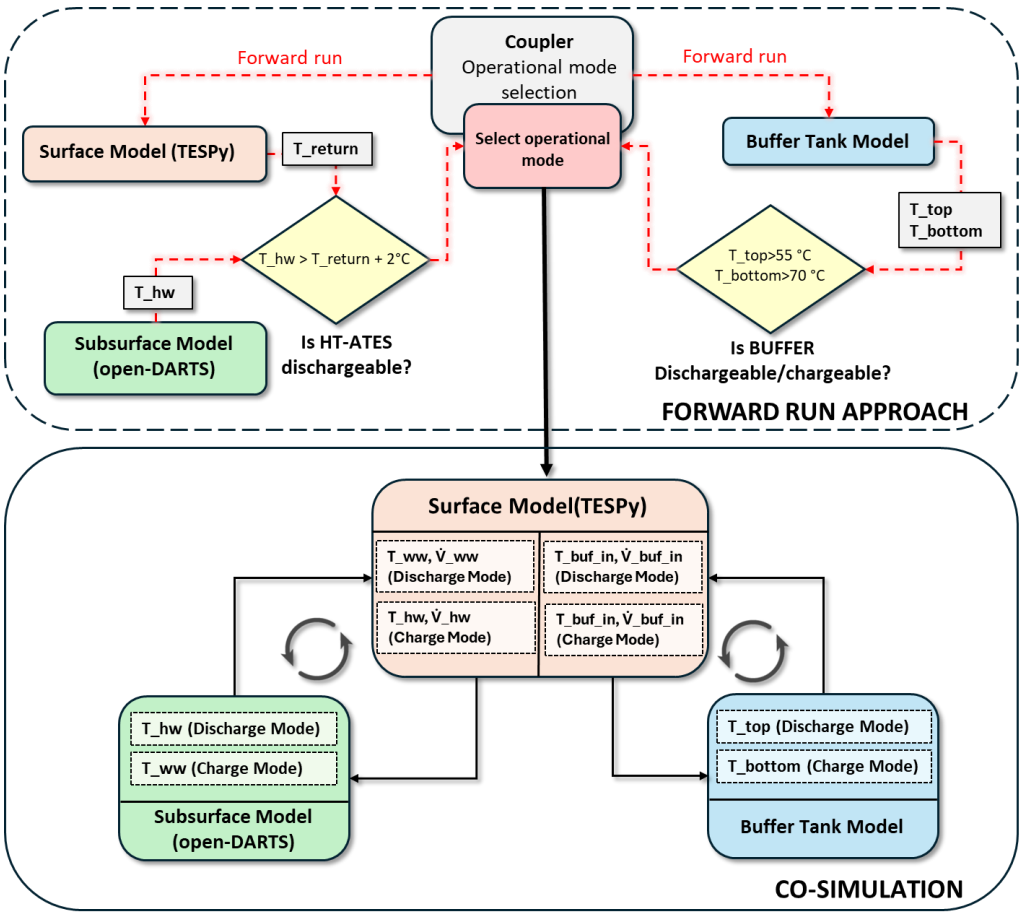


Figure 2. Workflow of the forward run approach and dynamic co-simulation framework. The co-simulation relies exchanging key variables between models: T_{hw} and T_{ww} represent hot and warm well temperatures, T_{return} is the network return temperature, T_{top}, T_{bottom} are the buffer tank temperatures and V denotes the flow rates for the respective components.

4 CASE STUDY – DELFT

The co-simulation framework is applied to the geothermal demonstration site in Delft, where heat is supplied to both the Delft University of Technology (TUD) campus and the city district heating network (OWD). The case study uses hourly heat demand together with measured supply and return temperatures from both networks, providing the boundary conditions for each simulation step. These data reflect the typical operation of the Delft heating system and capture the daily and seasonal variations relevant for assessing the combined operation of the geothermal doublet, HT-ATES system, buffer tank and auxiliary components.

4.1 Hourly Demand and Network Temperatures

Hourly heat demand profiles for both the TUD and OWD networks were constructed from the dataset shown in Figure 3. In earlier work (Kukrer et al., 2025), a sinusoidal daily demand representation was used to approximate seasonal fluctuations. In the present study, measured hourly variations are retained, allowing short-term peaks and rapid changes in network demand to be represented explicitly. These dynamics are important for flow-rate-based control, since the feasibility of charging or discharging depends directly on the combined return temperature from the two networks.

The total heating load of TUD and OWD combined is approximately 92,000 MW, with winter peak loads reaching about 40 MW. TUD generally exhibits higher peak demand, reflecting the larger share of older and less-insulated buildings on the campus.

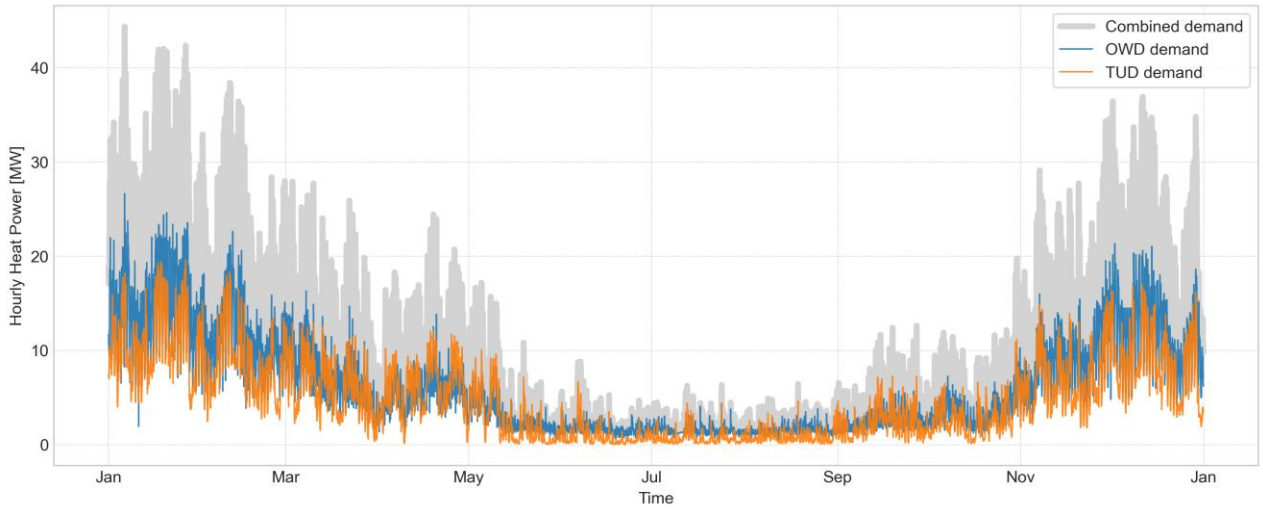


Figure 3. Hourly heat demand profiles for the TUD (orange) and OWD (blue) network, with the combined total load shown in the background (grey)

In addition to the heat demand time series, the dataset includes hourly supply and return temperatures for both networks. These temperatures vary with outdoor conditions and operational practices. Overall, supply temperatures range from 70–90 °C in winter and 55–70 °C in summer, depending on the network and outdoor temperature. Return temperatures generally fall within 35–55 °C, with TUD displaying slightly higher values during colder days due to higher heat losses from older buildings increase the demand and lead the system to operate at higher temperature levels. These hourly demand and temperature profiles serve as boundary conditions for the surface model and drive both the forward-run feasibility checks and the data exchange in the co-simulation framework.

4.2 Operational Modes

The heating system can operate in several different modes depending on the available geothermal production, the charge level of the buffer tank, the temperature of the HT-ATES wells, and the instantaneous heat demand from the TUD and OWD networks. Figure 4 presents the operational matrix , where *"CH"* denotes charging modes and *"D"* denotes discharging modes.

MODES	GEO	BOIL	BUFF*	ATES*
MODE CH1	●	○	○	●
MODE CH2	●	○	●	○
MODE D1	●	○	○	○
MODE D2	●	●	○	○
MODE D3	●	○	●	○
MODE D4	●	○	○	●
MODE D5	●	○	●	●
MODE D6	●	●	●	○
MODE D7	●	●	○	●
MODE D8	●	●	●	●

* ● *charge*
● *discharge*

Figure 4. Operational modes matrix. *'CH'* indicates *charging* modes, *'D'* indicates *discharging* modes. The specific mode is selected dynamically for each timestep based on the season and flow-rate thresholds of the components. Filled circles indicate active components in corresponding mode.

Geothermal heat is used as the baseload source whenever available. The buffer tank and the HT-ATES system add flexibility by covering short-term and seasonal imbalances. In this study, the buffer tank has a total volume of 1000 m^3 and a maximum charge/discharge flow of approximately 200 m^3/h, while ATES is charged only during summer using surplus geothermal heat, while discharging is carried out in winter when the hot-well temperature is sufficiently high to supply the network. The operational flow rate limit for HT-ATES is 275 m^3/h.

The control logic determines the active operational mode through a two-step decision process that combines seasonal definitions with flow-rate constraints:

1. Seasonal ATES control: The operational season defines the role of the long-term storage of ATES. In the summer, ATES system is set to charging mode where surplus heat is injected into the ATES hot well for storage. The buffer tank is not charged in this phase to prioritize the long-term storage. On the other hand, the ATES system is set to discharge mode in the winter period. It contributes to the network demand when geothermal capacity is insufficient. During winter, any instantaneous surplus heat due to low demand hours is directed to the buffer tank for short-term storage.

2. Flow-rate control: Within the seasons, the specific mode (Figure 4) is selected based on the total flow rate required by the district, source availabilities, and physical capacity thresholds of each source component.

- **Geothermal baseload:** The geothermal doublet has the first priority in the flow-rate hierarchy. If the demand flow rate is below the maximum geothermal production limit (375 m^3/h), the system operates in Mode D1, and surplus heat is stored in either of the storage options if available (e.g. CH1, CH2).
- **Storage discharge:** When the required flow exceeds the geothermal limit, the network needs additional sources. The system first utilizes the buffer tank (e.g. Mode D3) provided that the deficit is within the buffer's discharge limit of 200 m^3/h. If the demand exceeds this threshold or the buffer is not available, the HT-ATES is activated (up to limit of 275 m^3/h). If the demand is high enough to exceed the maximum capacity of geothermal and buffer, and both sources are available, buffer and HT-ATES can also be used together (e.g. Mode D5).
- **Peak/Backup:** The boiler is triggered as a last source (e.g. Mode D2, D6) only when the total flow demand exceeds the combined maximum flow thresholds of the geothermal, buffer, and ATES system, or when storage temperatures drop below usable cut-off temperatures.

Assessing these mode-switching thresholds is critical for the overall system performance. Since the activation of the fossil-fuel backup is directly related to the limitations of the other sources, the operational decisions defined by these thresholds determine the extent of fossil-fuel displacement. The interaction between seasonal storage, component flow limits, and variable network demand ultimately shapes the energy balance, demonstrating that successful HT-ATES integration depends not only on subsurface performance but also on surface-system control logic.

5 RESULTS

The co-simulation framework was applied over five consecutive annual cycles. The simulations start at the end of the charging season (late October), with the HT-ATES assumed to be fully charged at the beginning of Cycle 1. Each cycle represents a full charging-discharging season, allowing the long-term interaction between the geothermal doublet, the buffer tank, the HT-ATES wells and the district demand to be evaluated over multi-year operation.

Since the subsurface begins in a relatively cool initial state, the first year exhibits different behaviour from the later cycles(Figure 5). The hot-well temperature is not yet fully developed, meaning that ATES discharge is limited by the dynamic cut-off and the system relies more heavily on the heat pump and, during peak moments, the boiler. As the cycles progress, repeated charging increases the hot-well temperature and the wells approach a seasonal pattern. This leads to a growing contribution from HT-ATES, reduced reliance on auxiliary components, and a more stable balance between sources in winter.

The following subsections present the evolution of well temperatures, the annual contribution of each component, and the effect on boiler use and peak demand coverage.

5.1 Hot and Warm Well Temperature Evolution

Figure 5 shows the evolution of the hot-well and warm-well temperatures over five annual charge–discharge cycles. As the cycles progress, both wells gradually approach a stable thermal regime. The cycle-average hot-well outlet temperature during the discharge period increases from approximately 58°C in Cycle 1 to 62.6°C in Cycle 5. This long-term warming is a typical response of HT-ATES systems when operated repeatedly under similar annual loading conditions.

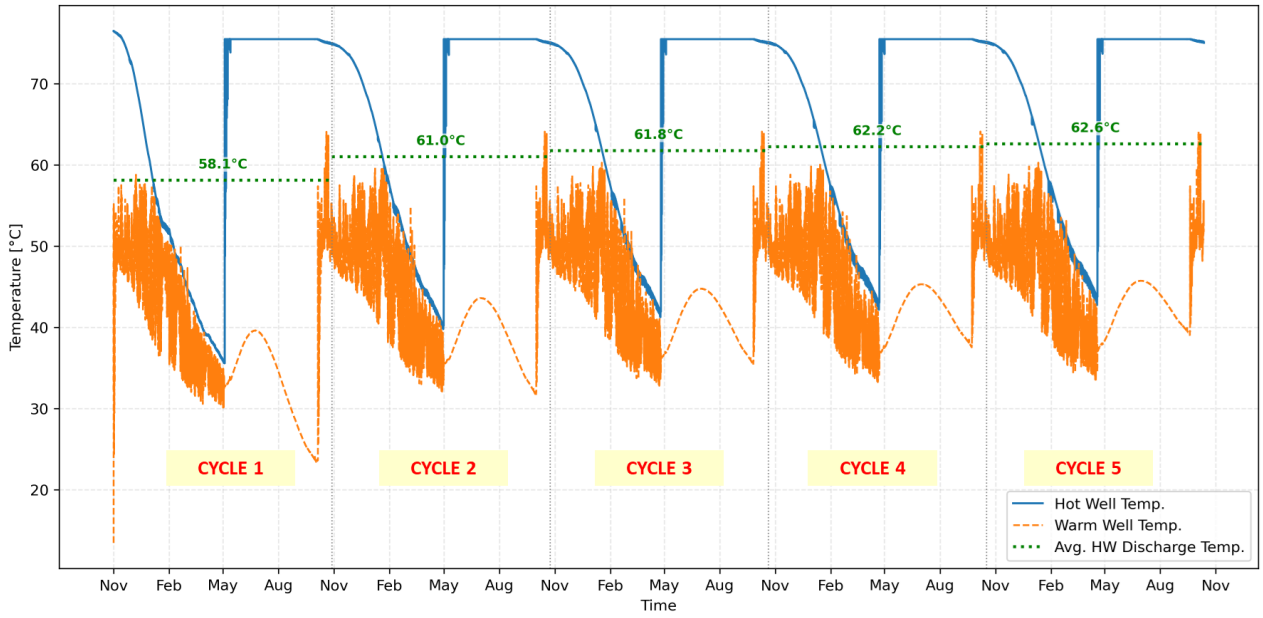


Figure 5. HT-ATES hot and cold well temperature evolution over five seasonal cycles.

As seen in Figure 5, short-term fluctuations in the warm-well temperature are more pronounced. These variations mainly occur during the discharge season and are a direct consequence of the dynamic cut-off control used in this study. Because the discharge decision is made by comparing the mixed return temperature of the district with the hot-well temperature, the system allows ATES extraction even when the hot-well temperature is marginally (2°C) above the return temperature. This increases the number of hours in which ATES can contribute, but it also introduces oscillations in the warm-well temperature depending on the return flow from the district.

A second effect becomes visible immediately after the discharge season (Figure 5). The warm-well temperature shows a small temporary rise before gradually cooling again. This peak reflects the thermal rebound caused by the earlier high-temperature injections during the charging season. As warm water from the outer parts of the aquifer slowly migrates back toward the well, it produces a short period of elevated temperature before the well returns to its long-term trend. These behaviours, such as seasonal oscillations, rebound effects, and gradual multi-year stabilization, are only captured because the system is evaluated through a fully dynamic co-simulation. The sequential interaction between the surface and subsurface models allows well temperatures to respond in real time to hourly operational decisions.

5.2 Annual Energy Contribution of the Sources

Figure 6 illustrates how the annual energy contributions from the different sources evolve across the five simulated cycles. Geothermal energy remains the dominant baseload throughout, supplying roughly 58–59 GWh which corresponds to roughly 65% of the total demand each year. This stable contribution reflects the continuous operation of the doublet and its prioritisation within the flow-rate-based control strategy.

The clearest shift occurs between seasonal storage and the fossil-fuel backup. As the HT-ATES system warms up over consecutive cycles, its annual discharge contribution increases markedly, from 11.4 GWh in Cycle 1 to 16.7 GWh in Cycle 5. This growth of about 47% is driven by increased temperature levels in the hot well, which raises re-injection temperatures and allows the controller to rely on ATES more frequently during winter peaks. This additional heat directly replaces boiler use. The annual boiler demand drops from 13.4 GWh in Cycle 1 to 7.8 GWh in Cycle 5, a reduction of roughly 42%. This indicates that after the initial operational years, the HT-ATES system can cover a significant share of the peak load that would otherwise be met by gas.

The compressor electricity demand shows only small variations (around 7.1–7.2 GWh), since it is mainly linked to the heat pump's steady operation rather than the seasonal storage behaviour. Buffer discharge remains minimal across all cycles, acting primarily as a short-term balancing element. Overall, the results highlight a substitution effect: geothermal heat stored in ATES progressively displaces fossil-fuel boiler peaks as the system reaches thermal equilibrium.

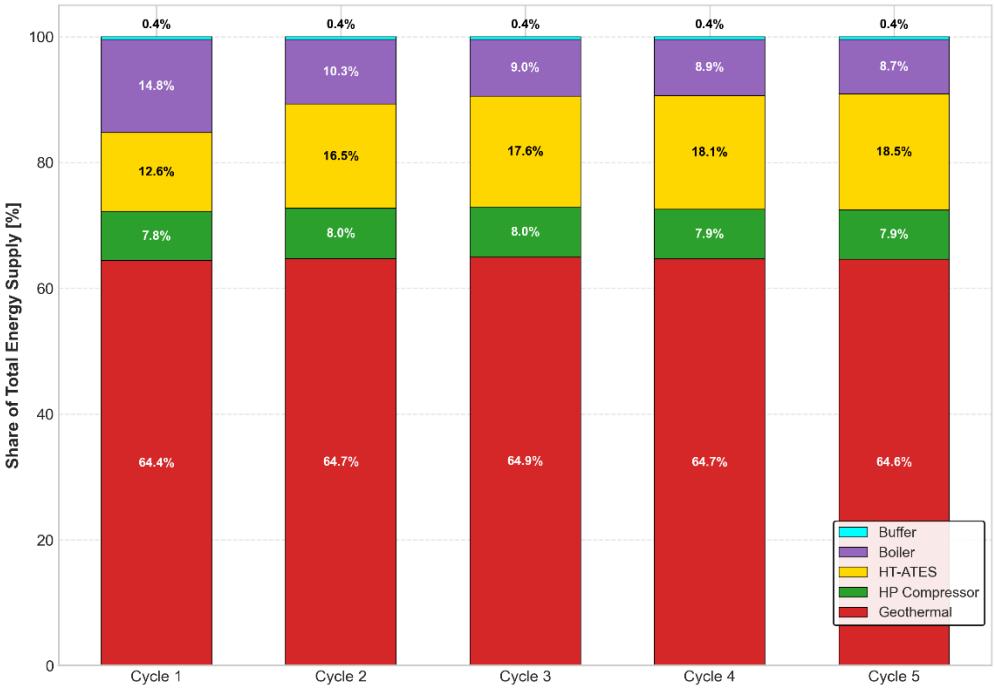


Figure 6. Share of annual energy supply by source across five simulation cycles.

5.3 Effect on Boiler Use and Peak Demand Coverage

Figure 7 shows how the balance between ATES discharge and boiler use evolves over the five simulated cycles. In Cycle 1, the boiler frequently covers the peak loads, especially during the coldest weeks of the heating season, while ATES contributes only intermittently. As the aquifer warms up over subsequent cycles, ATES becomes increasingly available at higher temperatures, and its discharge periods expand visibly across the winter months. By Cycle 5, ATES covers a substantial portion of the hourly peaks that were previously met by the boiler, resulting in shorter and fewer boiler activation periods. This gradual shift illustrates the thermal conditioning effect of the HT-ATES system and shows how stored geothermal heat progressively displaces fossil-fuel contribution.

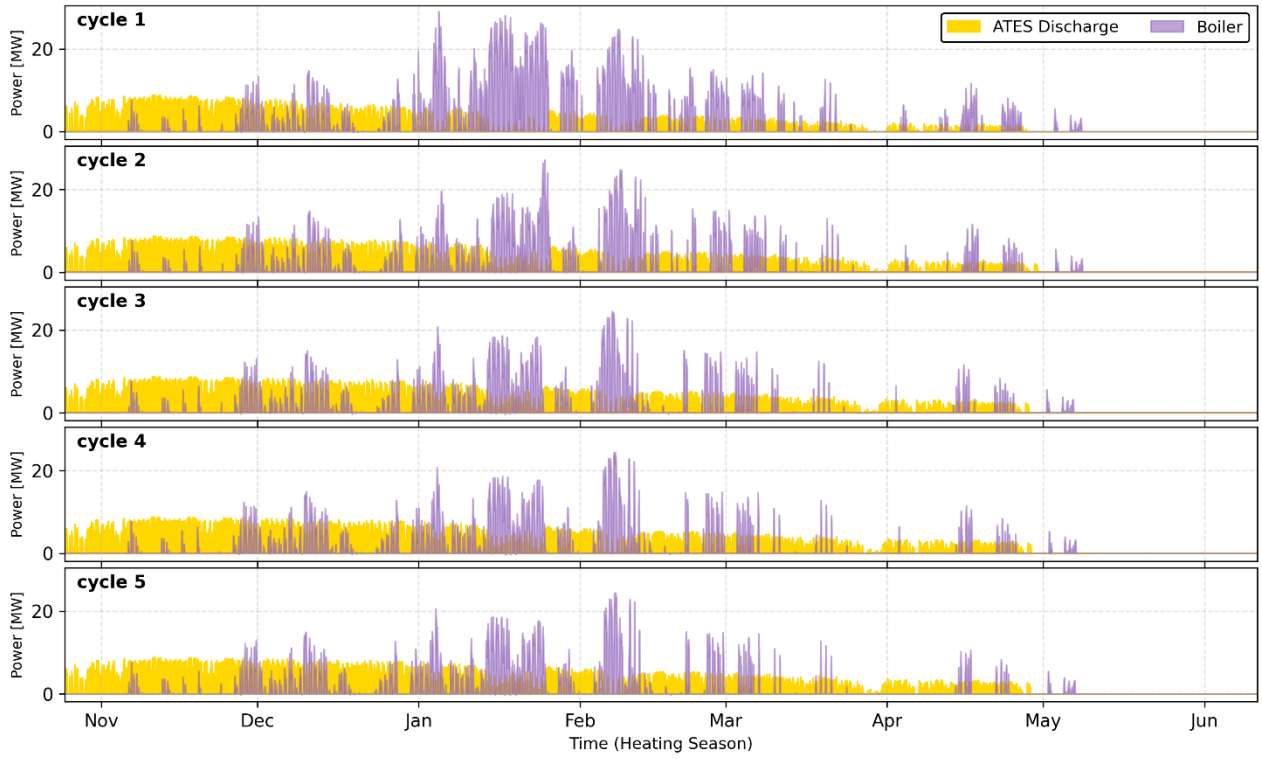


Figure 7. Hourly operation profiles of HT-ATES discharge and boiler per cycle.

6 CONCLUSIONS

This study presents a dynamic co-simulation framework to analyse the interaction between a geothermal doublet, an HT-ATES system, a stratified buffer tank, and a district heating network over 5 years. The main findings are:

- **Stable Geothermal Baseload:** The geothermal doublet remains the stable baseload source, supplying approximately 58–59 GWh per year across all cycles.
- **Increased HT-ATES Contribution:** The HT-ATES system contributes more with annual discharge rising from 11.4 GWh in the first cycle to 16.7 GWh in the last.
- **Fossil-Fuel Displacement**: Boiler demand declines from 13.4 GWh to 7.8 GWh (41.8% reduction), indicating that the HT-ATES unit can progressively help to reduce fossil-fuel peak supply.
- **Operational Dynamics:** Dynamic cut-off control enables ATES discharge even at relatively low hot-well temperatures, allowing early-winter use but also producing characteristic short-term warm-well fluctuations.
- **Thermal rebound effect**: A reversible thermal rebound effect is observed after each winter discharge period, where residual heat stored in the outer parts of the aquifer gradually migrates back toward the wells, temporarily increasing warm-well temperatures.
- **Limited short term storage:** The buffer tank's contribution remains limited due to its short-term balancing role. Its capacity smooths rapid fluctuations in return temperatures and flows, but it is not sized to deliver seasonal heat.

Overall, these results demonstrate that a fully coupled co-simulation approach is essential for capturing the complex system behaviour where multiple interacting components operate in conjunction. Future work will further examine alternative operational strategies, thresholds and assess system resilience under varying network and demand conditions.

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