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ATES Triplet Robustness for Varying Building Supply Temperatures

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INTRODUCTION

To achieve the required reduction in greenhouse gas emissions from the built environment, space heating and cooling needs to be decarbonized. Many technologies are decarbonizing by electrification, using electricity from Renewable Energy Sources. The misalignment between electricity uses and generation causes increased strain on the electricity grid, hence, energy storage is needed. Aquifer Thermal Energy Storage (ATES) ensures a steady supply temperature that is closer to the required temperature for heating, decreasing the electricity use of a heat pump when compared to a heat pump that uses the outside air as a source, yet still requires a substantial electrical input.

The ATES Triplet concept is designed to not require a heat-pump by using passive heating and cooling, thereby reducing the dependency on external electricity from the grid. The Triplet has on-site energy generation, with for instance solar heat collectors and dry coolers, two energy supply wells (hot and cold), and one additional well to balance flows and prevent thermal pollution of the energy supply wells. To evaluate whether this technology can supply heat and cold for a longer period, a detailed model study is presented here that models both the building energy system as well as the sub-surface flow and energy transport.

A previous study (van Esch et al., 2024) has shown that this concept can reduce overall and peak electricity use considerably when compared to a doublet for most buildings. This study evaluated the effect of five different building parameters on the pumping volumes and electricity use of the system. To do a largescale sensitivity analysis, the study decreased the complexity of the energy control system, utilizing only two modes of operation, which reduced the complexity of the energy management system that is needed to evaluate the long-term robustness. Such a complex energy management system model has been previous analysed (Wasman et al., 2024), which showed the operation of a Triplet to be complex, but feasible. That study, however, simplified the sub-surface, and did not show the effect of the complex operation on the performance of the wells, and could not accurately describe the robustness of the wells.

This study aims to assess the robustness of the Triplet for long-term operation and includes both a realistic energy infrastructure model, and a realistic subsurface model. A co-simulation approach is used where the sub-surface flow and energy transport model is integrated into an energy management model. With this combined model, the effect of varying injection temperatures for the hot well on the long-term performance of the ATES Triplet are simulated and evaluated.

METHOD

The complete modelling strategy is shown in Figure 1. The energy management system is modelled using TESpy (Witte & Tuschy, 2020). TESpy is a Python-based framework used to model the surface energy infrastructure. It solves the thermodynamic state of each component (e.g., heat exchangers, sources, etc.) by iteratively calculating pressure, temperature, enthalpy, and mass flow rate at every connection and component to achieve overall mass and energy balance within the network.

For our simulations, various TESpy network configurations were developed representing different operational states (including heating, cooling, charging, and discharging). The active mode is selected externally, with a decision tree structure, based on boundary conditions such as demand, outdoor temperature, available heat/cold generation, ATES well temperatures and availability. Once the appropriate configuration is called, it solves conditions for that timestep and returns the resulting flows, temperatures, and component energy rates (Figure 1). Heating systems typically have a required operating temperature, a maximum and a minimum temperature. Especially for floor heating, the delivered heat cannot be too hot. However, since the Triplet facilitates a disconnect between heat generation and use, a varied flow heat exchanger is used to decouple the supply temperature from the wells from the used temperature in the building. The result is a well injection

temperature that can be varied and set higher than the maximum supply temperature for the floor heating systems.

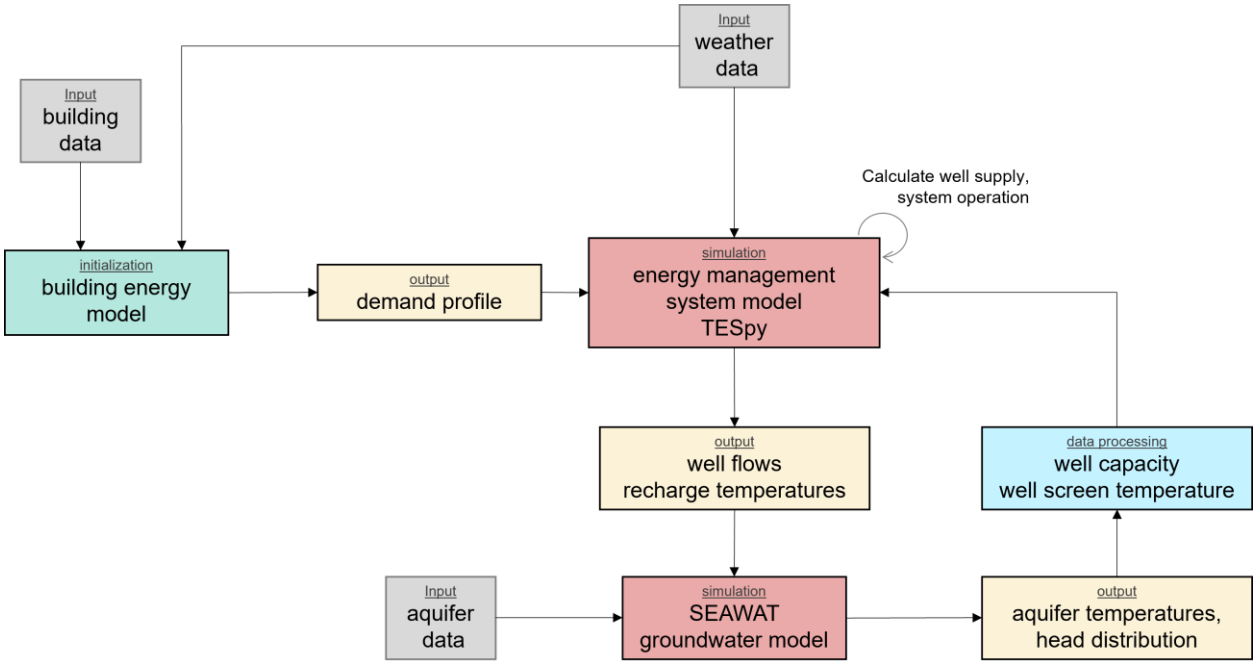


Figure 1. Schematic of the co-simulation model. Red boxes represent Simulation models, and the green box the building model. Grey boxes are their input, and yellow boxes represent the output. The blue box is a data-exchange step between the two simulation models.

To calculate the hourly heating and cooling demand profiles needed for input into the energy management system model, the EnergyPlus (U.S. Department of Energy, 2023) model is used, which requires meteorological data and building details as input. Typical Meteorological Years (Climate.OneBuilding, 2025) for the Netherlands are used. In this case, an energy efficient building is modelled, representing a five-story structure with a total floor area of approximately 18,000 m^2. The building complies with the Dutch standards ISSO 51/53 and NTA 8800 for high-performance buildings with an annular heating demand of about ≈3.35 TJ (≈ 926 MWh) and a cooling demand of ≈0.80 TJ (≈ 220 MWh).

To identify the flow required from the wells, a sub-surface model is used to calculate the flows and thermodynamic behaviour of the wells. The sub-surface model used is a SEAWAT model (Langevin, 2012). The required flow rates are based on the temperatures in the wells of the previous day. The model aggregates the hourly required flow from and to the wells and runs the sub-surface model with a daily timestep to calculate the flows since an hourly timestep would be too computationally intensive.

In this case, the SEAWAT model simulates a 30-meter sandy aquifer where the screens of the wells are placed, that has a horizontal hydraulic conductivity (K_h) of 10 m/d and a vertical conductivity (K_v) of 2 m/d. The aquifer is encapsulated with 30-meter clay aquitards on the top and bottom that have a K_h of 0.05 m/d and a K_v of 0.01 m/d. With the expected storage volumes these values result in well designs that are not overly susceptible to different losses (Beernink et al., 2024).

Three different scenarios are evaluated. These are based on different injection temperatures into the hot well: 45 °C, 60 °C and 75 °C. The demand figure, combined with the setpoint temperatures of the building, is used to calculate both the required injection and extraction volumes for the wells. The injection volume for the hot well is based on a lossless case, and then 30% is added to counteract losses and ensure a steady supply of heating. Cooling is also important, but since this is based on a Dutch scenario, groundwater temperature would still be cold enough to cool with. Therefore, the cold well is regenerated with the same amount of energy that is extracted, and losses are not negated. Furthermore, the hot well is seen as the limiting factor, and thus only the heating supply is evaluated in this study.

The evaluation is done based on the temperature variation in the hot well and the extracted volumes. It is assumed that the hot well can no longer supply the heating demand the moment the temperature dips under 35

°C. The system has a startup time, where not all energy can be supplied in a year. To evaluate the robustness under different injection temperatures, the first year where all energy can be supplied, thus the first year where the temperature does not drop under the 35 °C is identified. The injection and extraction patterns are shown to compare the required pumping volumes, which indicate the reliance of the Triplet on external electricity.

RESULTS

Figure 2 shows the average screen temperature in the hot well. The startup period where the heating demand cannot be met during the whole year can be clearly seen. Each year is seen as consisting of roughly three periods. One that is mainly charging, starting in April (where the temperature is constant at the injection temperature), one that is discharging and one that is a mixture of both. It is in this time where there is both charging and discharging that the temperature is seen to drop below the cutoff at the end of the first year. In the second year, the temperature drops below the threshold later in this mixed period. It can be observed that the wells become more stable each year, decreasing the size of the peaks and increasing the average temperature each year. Both the 60 °C and 75 °C scenarios reach the year where the system can fully meet the demand in year 6. The 45 °C scenario takes one more year to be able to provide the required heat.

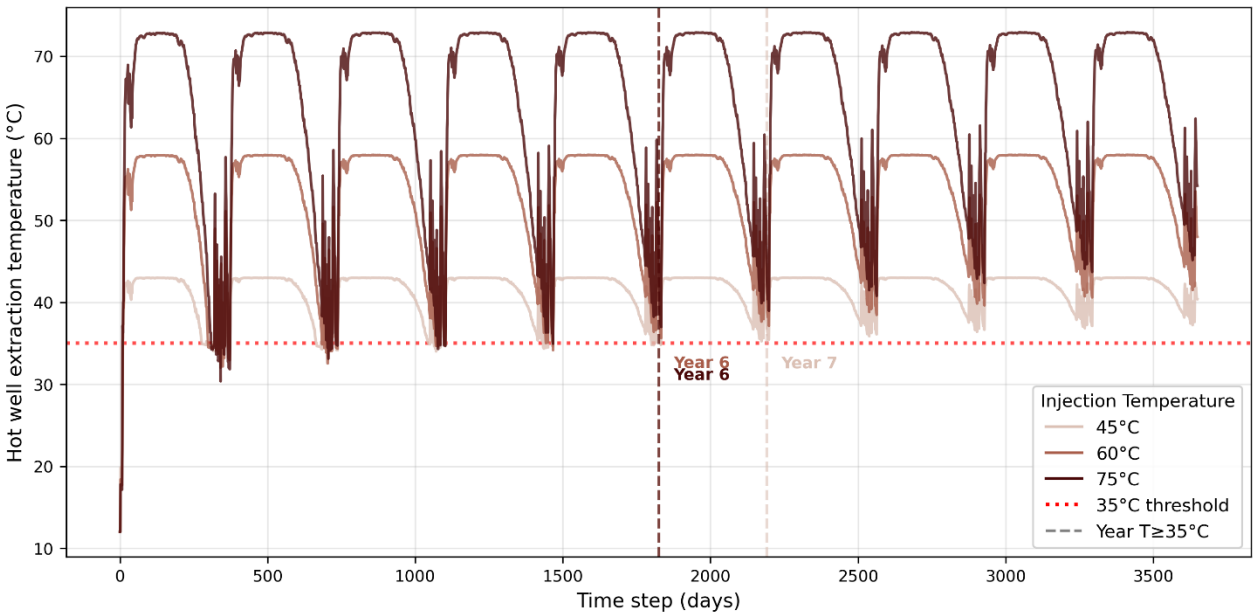


Figure 2. Temperature data for the 10-year run for the hot well, with three different injection temperature scenarios. The red dotted horizontal line indicates the threshold above which heating demand can be delivered.

The higher lowest temperature at the end of the 10 years for the 75°C scenario indicates that the system will be more robust in the long run, since it has a higher energy density, a higher average temperature in the well, and will thus be able to outlast systems with lower injection temperatures when a more extreme year follows.

Figure 3 shows that the higher injection temperature has the expected effect that less volume is required to deliver the same energy. As a result, the pumping electricity will go down for the hot well. The downside is that more energy and volume is required to regenerate the cold well, since water used to regenerate the cold well will have a higher temperature. External energy is required to regenerate the cold well, as dry coolers require electricity to operate, so that decreases the robustness of the system.

If all the injection volumes are added together for the final year, the 75°C scenario has the lowest total injection volume at 81 395 m^3, followed by the 60°C scenario with 87 571 m^3 and the 45°C scenario with 127 662 m^3. Though the cold injection is a bit higher when the hot well injection temperature is higher, the hot well injection volumes are much lower. It must be noted that, although the volume to be injected is lower, there is a downside to injecting such high temperatures. Firstly, the wells become more susceptible to heat losses, especially heat losses to the upper layers due to density effects (Beernink et al., 2026), and secondly, the required amount of solar heat collectors become more stringent, as a highly efficient heat collectors are required to always reach 75°C when injecting.

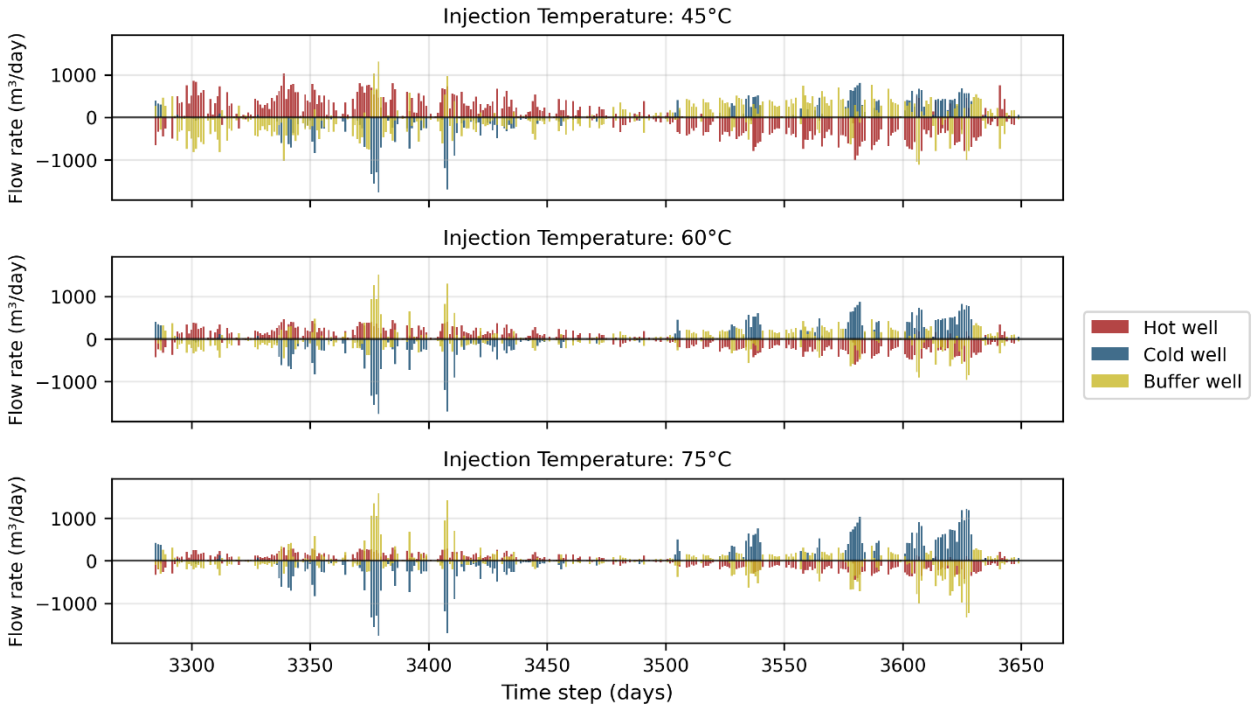


Figure 3. Injection and extraction flow rates for all three Triplet wells for the final year of the 10-year runs.

DISCUSSION AND CONCLUSION

The increase in excess energy in the hot well of the ATES Triplet increases the robustness to providing the heating over time. However, in the first years after installation, it may not be able to provide all the required heat in the later parts of the heating season. This study shows that a disconnect between the heating supply temperatures and the injection temperatures into the hot storage well ensures a more robust system. This disconnect facilitates higher injection temperatures in the hot well which leads to a shorter startup time, and a higher energy density in the well which decreases the required pumping volume for the system and thus decreases the reliance on grid electricity.

This study shows that a co-simulation model is able to model a heating and cooling system in detail, with all the operational modes and a detailed sub-surface model. The co-simulation allows to evaluate the effect of robustness on both the energy management system and the sub-surface model. The model, however, is computationally intensive, so simplifications must be made carefully, to ensure an efficient runtime whilst simultaneously ensuring a reliable result.

To fully answer the question whether or not the Triplet can run robustly, a wide range of conditions must be assessed. This study is the starting point to answer that question. Not only should the injection temperature be varied, but to truly assess the robustness of the system, more extreme climate data should be tested, focusing on a multi-year period of extreme summer or winters. Furthermore, in this study the injection volumes are based on a fixed percentage on top of the heating demand requirements. Varying this percentage could ensure a quicker startup, and a lower heat generation need in the later years. This could be achieved with the temporary incorporation of a heat pump or another form of added heat. This would increase the reliance on local energy grids in the startup but decrease the required heat generation facilities.

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