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Ultra-High-Temperature Underground Thermal Energy Storage (UHT-UTES) for Large-scale, Inter-seasonal Electricity Storage

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ABSTRACT

Renewable energy generation suffers from seasonal intermittency which requires very large storage capacity to align supply and demand. Underground Thermal Energy Storage (UTES) in abandoned hydrocarbon reservoir and deep saline aquifers offers storage capacity at the required scale, given the very large available storage volume. This study investigates the potential of ultra-high temperature underground thermal energy storage (UHT-UTES) to balance renewable electricity supply and demand. Preliminary simulations show that UHT-UTES can potentially provide a seasonal recovered storage capacity of 10's GWh_{th} per well doublet. The thermal recovery efficiency gradually improves over system operation, and can reach ca. 90% after 20 years of operation. Storage efficiency is primarily controlled by conductive heat losses during inter-seasonal storage, which are limited by the low thermal conductivity of rocks. Future studies will focus on introducing geological heterogeneity in reservoir models, optimising the round-trip efficiency of electricity generation, and addressing potential chemical reactions and other potential risks to sustainable operation.

1 1. INTRODUCTION

Renewable energy sources such as wind and solar are intermittent due to seasonal fluctuations in supply. The offset between supply and demand is causing increasingly frequent renewable supply curtailment across Europe. Energy storage can balance supply and demand, but seasonal storage at scale requires very large capacity. Underground thermal energy storage (UTES) offers such capacity, because of the very large available storage volumes.

Low-temperature (LT-) UTES systems are commonly used to provide heating and cooling (e.g. Fleuchaus et al. 2018) while high temperature (HT-) UTES systems can provide direct heating without the use of a heat-pump (Stricker et al. 2020). Storage temperatures in even HT-UTES are typically <100°C. Here, we investigate the potential for ultra-high temperature (UHT-UTES) to balance seasonal fluctuations in electricity supply and demand. During periods of excess supply, UHT-UTES operates in "storage mode": groundwater is pumped via the warm well(s) from naturally porous, permeable underground aquifers at depths >500 m, heated to high

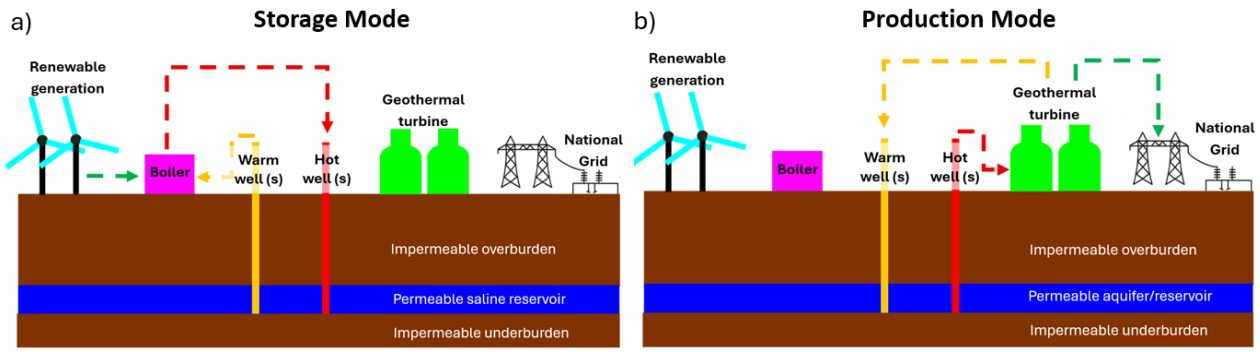


Figure 1. Schematic showing the operation of UHT-UTES. a) denotes the storage mode during which water is produced from warm well, heated using excessive renewable energy and injected into hot well for storage. b) denotes the supply mode during which stored hot water is produced from hot well and used to drive electricity generation through geothermal turbine. The rejected warm water from the turbine is injected via the warm well and stored until the next storage mode.

temperature (>150°C) and pumped back underground via the hot well(s) where it is stored (Fig. 1a). When demand exceeds renewable supply, UHT-UTES switches to "production mode": the high temperature water is pumped back to surface via the hot well(s) and used in geothermal turbines to generate electricity. The rejected water from the turbines is injected back into the aquifer via the warm well(s) where it stored for the next storage mode.

UHT-UTES offers several potential advantages over comparable underground storage technologies such as hydrogen storage: the surface facilities are conventional, comprising boilers and turbines, and expertise can be shared from hydrothermal electricity production. The technology can utilise deep saline aquifers and end-of-life hydrocarbon reservoirs which are geographically widespread and offer large storage and flow capacity. Despite the potential for UHT-UTES, significant uncertainties remain concerning storage efficiency when the stored water temperature is significantly higher than the ambient reservoir temperature. There are also potential risks to sustainable operation, such as scaling and associated loss of storage and flow capacity, and/or the potential for rock weakening and seismicity.

This study uses numerical simulation to assess the potential of storage efficiency of UHT-UTES in a deep saline reservoir. Thermal energy stored and recovered in each injection-production cycle is modelled to estimate both capacity and storage efficiency of UHT-UTES. Sensitivity tests are performed to quantify the variation in storage efficiency.

2 METHOD

2.1 Modelling Approach

Simulation of UHT-UTES operation requires solution of the coupled equations governing flow and transport in porous media. Here, we use the open-source Imperial College Finite Element Reservoir Simulator (IC-FERST, available at https://multifluids.github.io; Regnier et al., 2022). Dynamic Mesh Optimisation (DMO) is applied to accurately resolve the groundwater plumes formed in the reservoir at lower computational cost compared to conventional fixed-mesh approaches (Salinas et al. 2021).

2.2 Quantifying Storage Efficiency

UHT-UTES operates using one or more hot and warm well doublets (Fig. 1). The thermal recovery efficiency (R_T) of the hot or warm wells is defined as the ratio of thermal energy recovered from the well(s) during production to the energy stored in the preceding injection period (Sommer et al. 2013):

$$R_T = \frac{E_{ex}}{E_{in}} = \frac{\int_{ex} q_p (T_p - T_{aq})\, dt}{\int_{in} q_i (T_i - T_{aq})\, dt} \qquad [1]$$

where *E* denotes energy, subscript *ex* denotes extraction, subscript *in* denotes injection, q_i and q_p are the volumetric flow rates during injection and production, T_i is the injection temperature (also known as the storage temperature), T_p is the production temperature at the wellhead, and T_{aq} is the average unperturbed aquifer temperature. The storage efficiency of UHT-UTES is defined as

$$\eta = \frac{\int_{ex} q_p (T_{p,h} - T_{i,w})\, dt}{\int_{in} q_i (T_{i,h} - T_{p,w})\, dt} \qquad [2]$$

where $T_{i,h}$ and $T_{p,h}$ denote the wellhead temperatures of the hot well during storage and production, and $T_{i,w}$ and $T_{p,w}$ denote the corresponding wellhead temperatures of the warm well.

2.3 Model Setup

The reservoir model is shown in Fig. 2. The storage reservoir comprises a homogeneous, saline aquifer located at 1000 m depth. The three-dimensional (3D) model has dimensions 5000×5000×2100 m and comprises three layers: the 100 m thick aquifer, between two 1000 m thick impermeable mudstone layers. Injection and production is via two 0.25 m diameter wells connecting the reservoir to the surface. The injection and production rates for both wells are set to be 13.85 L/s, which is in line with typical flow rates for deep reservoirs. The production rate ensures that the mass of water injected and produced is the same. The well spacing of 1 km is chosen to be much larger than the maximum thermal radius (R_{th}) across all the simulation cases tested, to avoid thermal interference. The thermal radius is given by (Doughty et al. 1982)

$$R_{th} = \sqrt{\frac{c_{p,f} * \rho_f * V_i}{((c_{p,f} * \rho_f) * \phi + (c_{p,r} * \rho_r) * (1 - \phi)) * \pi * L_s}} \qquad [3]$$

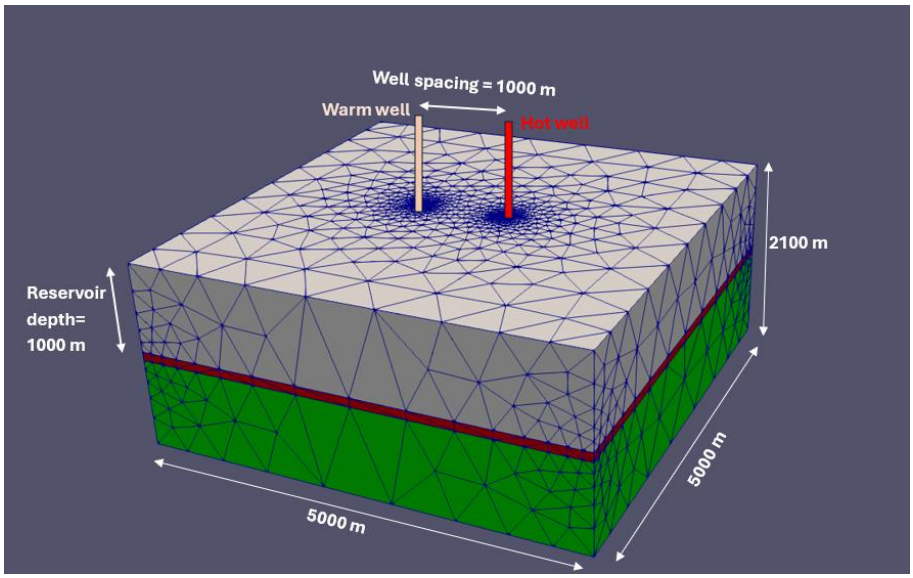


Figure 2. Initial 3D unstructured mesh representing the reservoir geometry: a 5000×5000×2100 m domain with 3 vertical layers. The permeable, homogeneous aquifer (red) lies between two impermeable layers at 1000 m depth. The hot well (red) and warm well (brown) connect the aquifer to surface with a well spacing of 1000 m.

where $c_{p,f}$ and $c_{p,r}$ are specific heat capacities for water and rock, ρ_f and ρ_r are densities for water and rock, ϕ is the porosity, V_i is the volume of water injected and L_s is the well screen length that is open to flow. The maximum R_{th} estimated for the cases tested here is 31.2 m.

The aquifer is initially fully saturated with groundwater, with salinity of 0.15 kg/kg, at hydrostatic equilibrium. The surface temperature is fixed at 25°C, and a typical geothermal gradient of 25°C/km is applied. Hydrostatic pressure boundary conditions are applied at the lateral model boundaries; the top and bottom boundaries are closed for flow.

This study considers UHT-UTES to operate annual cycles of 6-months injection followed by 6-months production continuously for 20 years. Five different $T_{i,h}$ are experimented between 150°C and 250°C. $T_{i,w}$ would generally be determined by the outlet temperature of geothermal turbine. Here we consider a simplified setting that all thermal energy recovered are utilised, so the rejected water from the geothermal turbine has the same temperature as the reservoir. Hence, $T_{i,h} = T_{aq}$ and $R_T = \eta$ in this study.

3 RESULTS

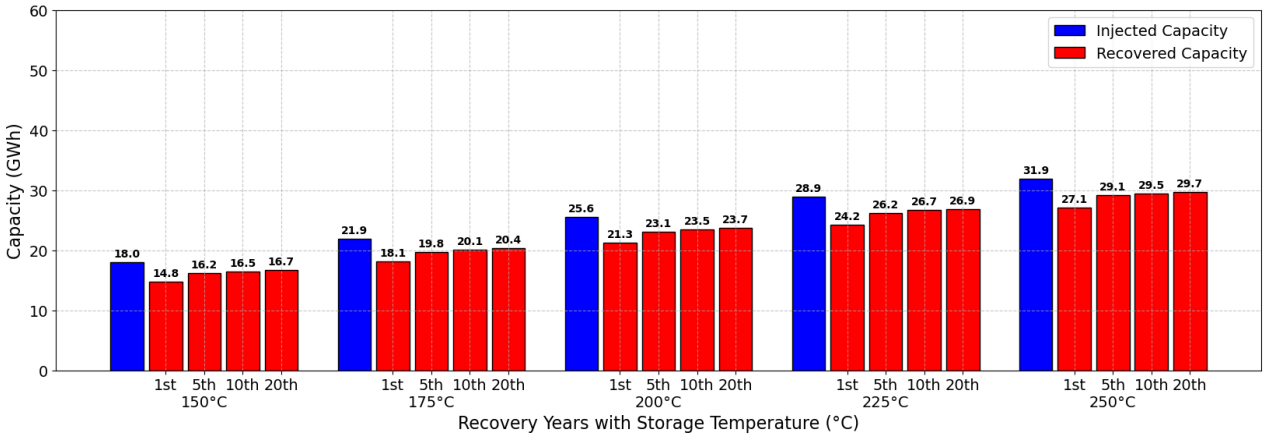


Figure 3. Stored ($E_{th,i}$) and recovered energy capacity ($E_{th,p}$) of the hot well, for storage temperatures spanning 150 °C to 250 °C after the 1st, 5th,10th and 20th storage and production cycles.

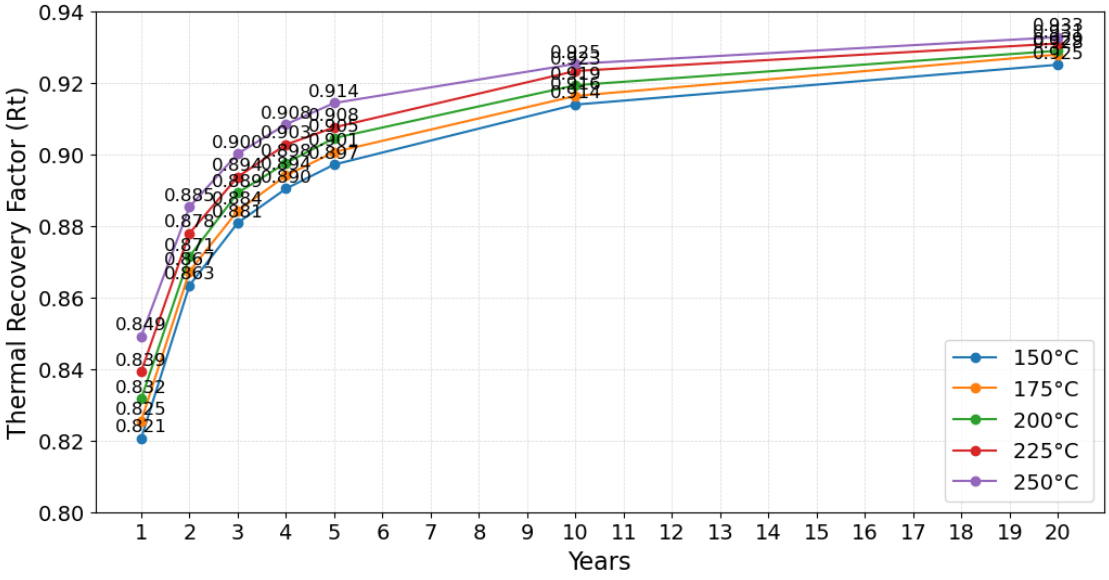


Figure 4. R_T of UHT-UTES with storage temperatures ranging over 150 °C to 250 °C. R_T consistently improves during operation, reaching 0.93-0.94 after 20 years. Higher storage temperatures generally yield higher R_T.

3.1 Reference Case Storage Potential

Reference case simulations suggest that UHT-UTES could achieve a recovered capacity of 18-31.9 GWh_{th} per hot well on a seasonal basis (Fig. 3). Initially, R_T for the hot well ranges between 0.82-0.85 after the first injection and production cycle. Recovery then improves as the reservoir warms in response to storage, reaching 0.914-0.925 after ten years of operation, and 0.925-0.933 after twenty years (Fig 4). Notably, higher R_T is obtained for higher storage temperatures; although absolute thermal losses are higher at higher storage temperatures, they are smaller in proportion to the total stored thermal energy.

3.2 Parametric Tests

Parametric tests, comprising variations in a range of physical and operational parameters, were used to study the sensitivity of recovery efficiency. Changing parameters potentially modifies the heat transfer mechanisms in the reservoir. We use two dimensionless numbers to quantifying heat transport: the Rayleigh Number (Ra) represents the ratio of thermal convection to diffusion (Turcotte & Schubert, 2002):

$$Ra = \frac{g k_z (\rho_{h,i} - \rho_{aq}) H}{\phi \mu D} \qquad [4]$$

where g is gravity, k_z is vertical permeability, H is the aquifer thickness, μ is the fluid viscosity and D is the aquifer thermal diffusivity. The transverse buoyancy number ($N_{b,t}$) is used to compare the relative importance of buoyancy and forced advection (Debbabi et al. 2018):

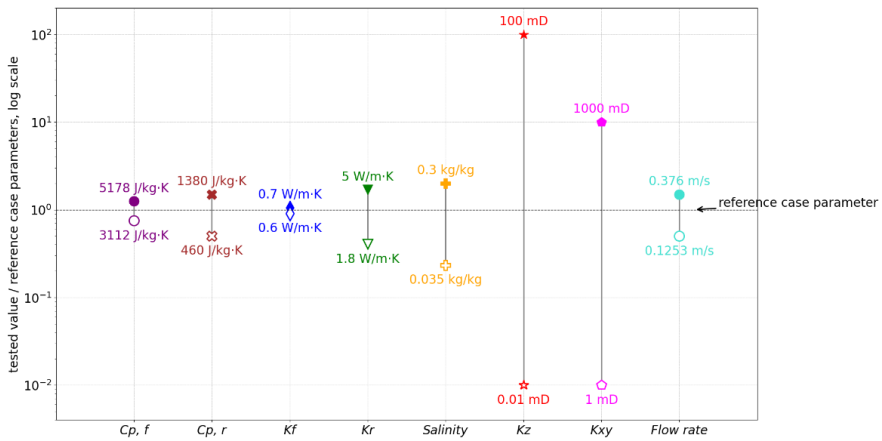


Figure 5. Parameters varied and the range explored in the parametric tests.

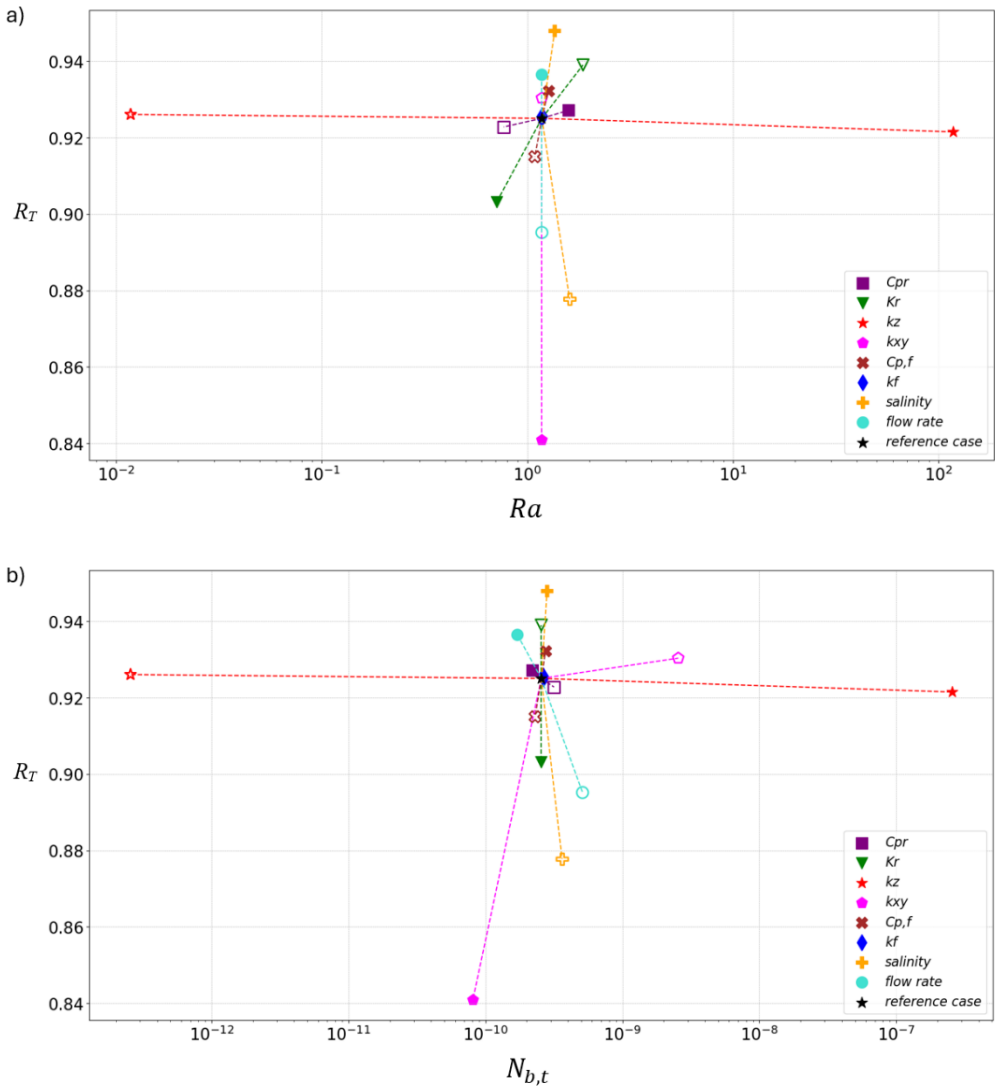


Figure 6. Results of parametric test using a storage temperature of 150 °C. a) show R_T as a function of Ra for parametric tests. B) shows R_T as a function of $N_{b,t}$ for parametric tests using a storage temperature of 150 °C.

$$N_{b,t} = \frac{g k_z (\rho_{h,i} - \rho_{aq}) \cdot \cos(\theta) R_{th}}{\mu q_{plume} H} \cdot \left(\frac{k_z}{k_{x,y}}\right)^{0.5} \qquad [5]$$

where θ is the dip angle of reservoir, $k_{x,y}$ is the horizontal permeability and q_{plume} is the velocity at which the plume expands radially, given by:

$$q_{plume} = \frac{q_i}{\pi \cdot R_{th}^2} \qquad [6]$$

Parametric tests were conducted for UHT-UTES operating in the homogeneous aquifer with a storage temperature of 150 °C. Parameter variations are summarised in Fig 5. Fig. 6 shows R_T as a function of Ra. A positive correlation is observed for thermal parameters, such as rock and water thermal conductivity and heat capacity, suggesting higher thermal losses are caused by larger conductive heat transport. Increased vertical permeability (k_z) enhances vertical water flow and the impact of buoyancy thereby reducing R_T, but its impact is moderate compared to the variations caused by thermal properties.

Fig. 7 shows the R_T as a function of $N_{b,t}$. Varying $c_{p,f}$, flow rate and k_z returns a negative correlation between R_T and $N_{b,t}$, suggesting that a relatively higher contribution from buoyancy lead to higher thermal losses. Conversely, varying horizontal permeability ($k_{x,y}$) returns a positive correlation. This is caused by the pressure

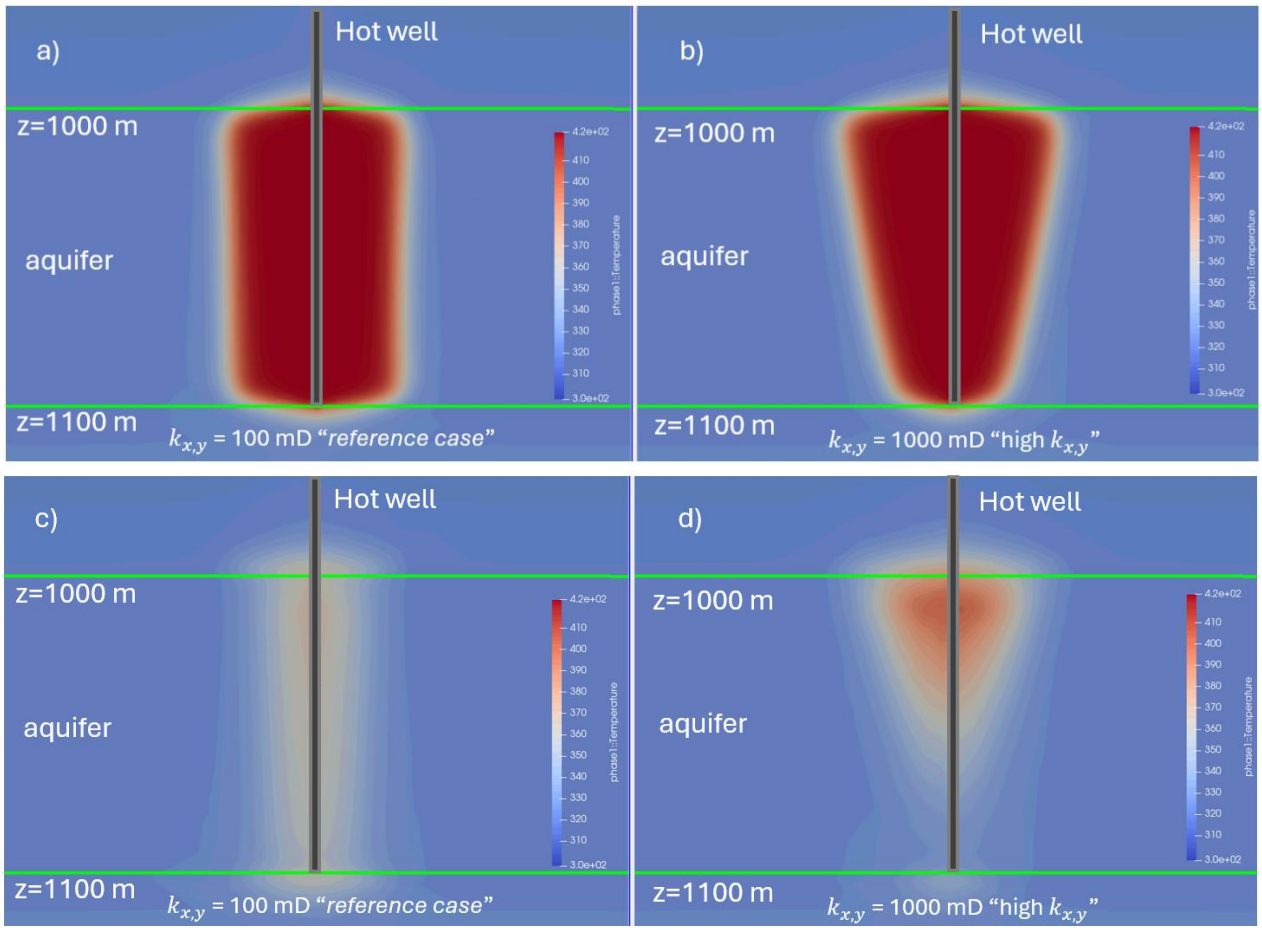


Figure 7. Impact of horizontal permeability on the hot plume morphology. a) and b) show the maximum plume formed under the hot well of the reference case and high $k_{x,y}$ parameter test, where high $k_{x,y}$ leads to more significant plume migration from the reference case. c) and d) shows the minimum plume by the end of production mode, where high $k_{x,y}$ case shows more remnant heat unproduced at the top of aquifer as a result of the plume migration.

decrease from the upper to the lower part of the well, which leads to injected heated water spread further into the aquifer at shallower depths than the deeper depth. As a result, the "high $k_{x,y}$" test case would lead to more prominent shape migration under the hot well than the "reference case", and more remnant thermal water left in the reservoir (Fig. 7 b), resulting in lower R_T.

3.3 Potential Round-trip Efficiency of Electricity Storage

This study has demonstrated that the storage efficiency of thermal energy in UHT-UTES reaches ca. 90%. Consequently, the overall round-trip efficiency for electricity storage via UHT-UTES is likely to be primarily constrained by the conversion efficiency of geothermal turbines, which typically ranges from a few percent to about 18% (Zarrouk and Moon, 2014). The round-trip efficiency can be maximized by selecting a storage temperature that optimizes turbine efficiency while minimizing storage losses. Further improvements in turbine efficiency can be achieved by selecting suitable inlet pressure drops and enforcing a minimum production cut-off temperature. Future work will investigate optimum operational parameters to maximize the round-trip storage efficiency.

4 CONCLUSION

UHT-UTES can potentially store thermal energy of the order of 10's GWh_{th} per doublet on a seasonal basis, with thermal recovery efficiency from the hot well reaching ca. 90% after 20 years of operation. The storage potential of UHT-UTES can be scaled up by deploying multiple doublets in the same reservoir, or across multiple reservoirs. Storage of multiple TWh_e on a seasonal basis could be achieved using of order 100s of doublets targeting storage aquifers and reservoirs at a few km depth; for comparison, over 8000 wells have been drilled to similar depth in the UK Continental Shelf of the North Sea. UHT-UTES is a promising technology for mitigating renewable intermittency. Higher thermal recovery efficiencies are associated with higher storage temperatures.

Parametric tests indicate that thermal losses result from both conduction and convection, although the storage efficiency vary <10% compared to the reference case scenario. Heterogeneity might impact plume migration and introduce further thermal losses. Turbine conversion efficiency, rather than storage efficiency, is likely the major limitation on the round-trip efficiency of electricity generation. Future research will focus on understanding the influence of heterogeneity on plume migration, optimizing storage and round-trip efficiency through engineering approaches, investigating the potential chemical reactions and reactive flow induced by storage and addressing operational obstacles and geohazards.

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