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Optimal energy production and density for ATES and open-loop geothermal systems

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INTRODUCTION

Aquifer Thermal Energy Storage (ATES) and open-loop unidirectional Groundwater Heating and Cooling (GWHC) systems can supply sustainable, low carbon heating and cooling to the built environment. Both technologies employ borehole doublets and have similar installation and operational costs. However, the seasonal reversal of ATES systems allows for the capture and re-use of energy that is wasted in GWHC systems, offering the potential for higher efficiency.

Numerous studies have shown that energy production from GWHC and ATES systems is maximized if thermal interference and thermal breakthrough are avoided. This is typically achieved by implementing a minimum borehole spacing which, in some jurisdictions, is a licensing requirement (Bloemendal et al., 2018a). For example, in The Netherlands, boreholes in ATES installations must have a minimum spacing of $3R_{th}$, where R_{th} is the thermal radius, given by (e.g. Doughty et al., 1982)

$$R_{th} = \sqrt{\frac{c_w V_i}{c_{aq} \pi L}} \qquad [1]$$

where c_w is the water volumetric heat capacity, c_{aq} is the aquifer volumetric heat capacity, V_i is the total volume of injected groundwater, and L is the screen length.

Borehole doublets are typically separated laterally to avoid interference between the thermal plumes created in the aquifer (e.g. Bloemendal et al. 2018a,b). However, this design can yield low energy density (energy delivered per unit land area) because the system has a large areal footprint. Energy demand per unit area in densely populated urban areas may be high (e.g. Bayer et al., 2019), such that energy density becomes an important system design criterion. Sites with small surface area but large demand may also be better served by systems that offer high energy density. In thick aquifers, energy density could be increased by separating plumes vertically, installing shorter borehole screens at different depths.

The aim of this study is to establish a framework to systematically determine the impact of a wide range subsurface and design parameters on GWHC and ATES system performance. In the results reported here, we assume homogeneous aquifer properties and no groundwater flow, to establish a baseline for future investigation. Aquifer permeability anisotropy is considered as an uncertain aquifer property. The lateral spacing of boreholes, borehole screen length and vertical offsetting of screens are considered as key design decisions. We focus on energy produced, and energy density, as key system performance metrics.

METHODS

We assume a confined, homogenous aquifer which is 100 m thick. The horizontal permeability is 1000 mD and the porosity is 20 %. We assume no groundwater flow. Borehole flow rates are fixed at 50 m3/hr. Cool water injected during heating periods has a constant temperature of 8°C; warm water injected during cooling periods has a constant temperature of 18°C. The initial ambient aquifer temperature is 13°C. We simulate system operation for 10 years. In each year, we assume heating for 4 months and cooling for 4 months, separated by rest periods of 2 months. We simulate operation of a single doublet.

The aquifer vertical permeability is varied across simulation cases over the range 1 – 1000 mD. The borehole spacing is varies over the range 0 – 500 m, and the screen length in each borehole is varied over the range 10 – 100 m. The vertical screen separation is varied over the range 0 – 90 m. We use a simple Monte-Carlo sampling strategy to create 840 unique models, with values drawn from the input ranges. GWHC and ATES operation in each model is then simulated, yielding a total of 1680 simulation cases. It is assumed that the target borehole rates can always be delivered (i.e. we do not impose maximum pressure change limits) although checks suggest

that pressure changes are reasonable across all cases. Balanced operation (equal delivery of heating and cooling) is ensured by design.

To calculate the energy density, we estimated the area occupied by the system as the area of the smallest rectangle that encompasses the outer limits of the maximum extent of the thermal plumes for the final cycles of heating and cooling (Stemmle et al., 2024). The outer limits of the plumes were defined by a temperature change of 0.5°C from the initial aquifer temperature. System operation was simulated using the open-source Imperial College Finite Element Reservoir Simulator (IC-FERST, available at https://multifluids.github.io; Salinas et al. 2021; Regnier et al., 2022).

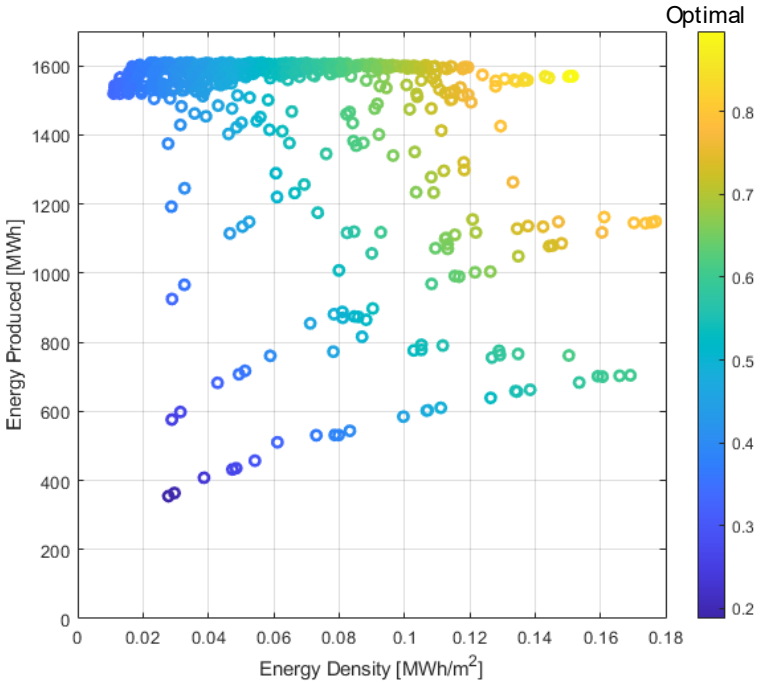


Figure 1: Energy produced versus energy density across all ATES scenarios. Datapoints coloured by optimal combined production (equation [2])

RESULTS

We begin by considering the total heating and cooling energy delivered per cycle by ATES after 10 years of operation. Energy delivered increases with increases lateral borehole spacing and screen offset, consistent with increased thermal recovery as a result of reduced thermal interference of the plumes in the aquifer, which are well separated either laterally or vertically. A longer screen length slightly increases the energy delivered, particularly for the lower values. There is little sensitivity to vertical permeability.

We now consider the energy density offered by ATES. Energy density decreases with increased lateral borehole spacing, because the plumes occupy a larger area. The highest values of energy density also decrease with increasing vertical screen separation and decreasing screen length. Large vertical screen separation requires shorter screen length. In both cases, plume area increases. There is little sensitivity to vertical permeability.

We calculate the normalised combined energy and energy density delivered as

$$O = \sqrt{\frac{E_p}{E_p^{max}} + \frac{E_d}{E_d^{max}}} \qquad [2]$$

where E_p denotes energy produced, E_d denotes energy density, and the superscript max denotes the largest values obtained. Figure 1 cross-plots E_p and E_d, with the data coloured by the combination O. We identify the optimal simulation case with the highest combined E_p and E_d (highest O) in the top right corner.

The optimum simulation case has the longest possible well screen length for both boreholes, and the boreholes are spaced at slightly less than $2R_{th}$ (Figure 2). Higher energy density is possible, but the highest energy density case produces only 72% of the energy produced by the optimum case (Fig. 1). Likewise, higher energy production is possible, but the highest energy production case offers only 12% of the energy density of the optimum case (Fig. 1).

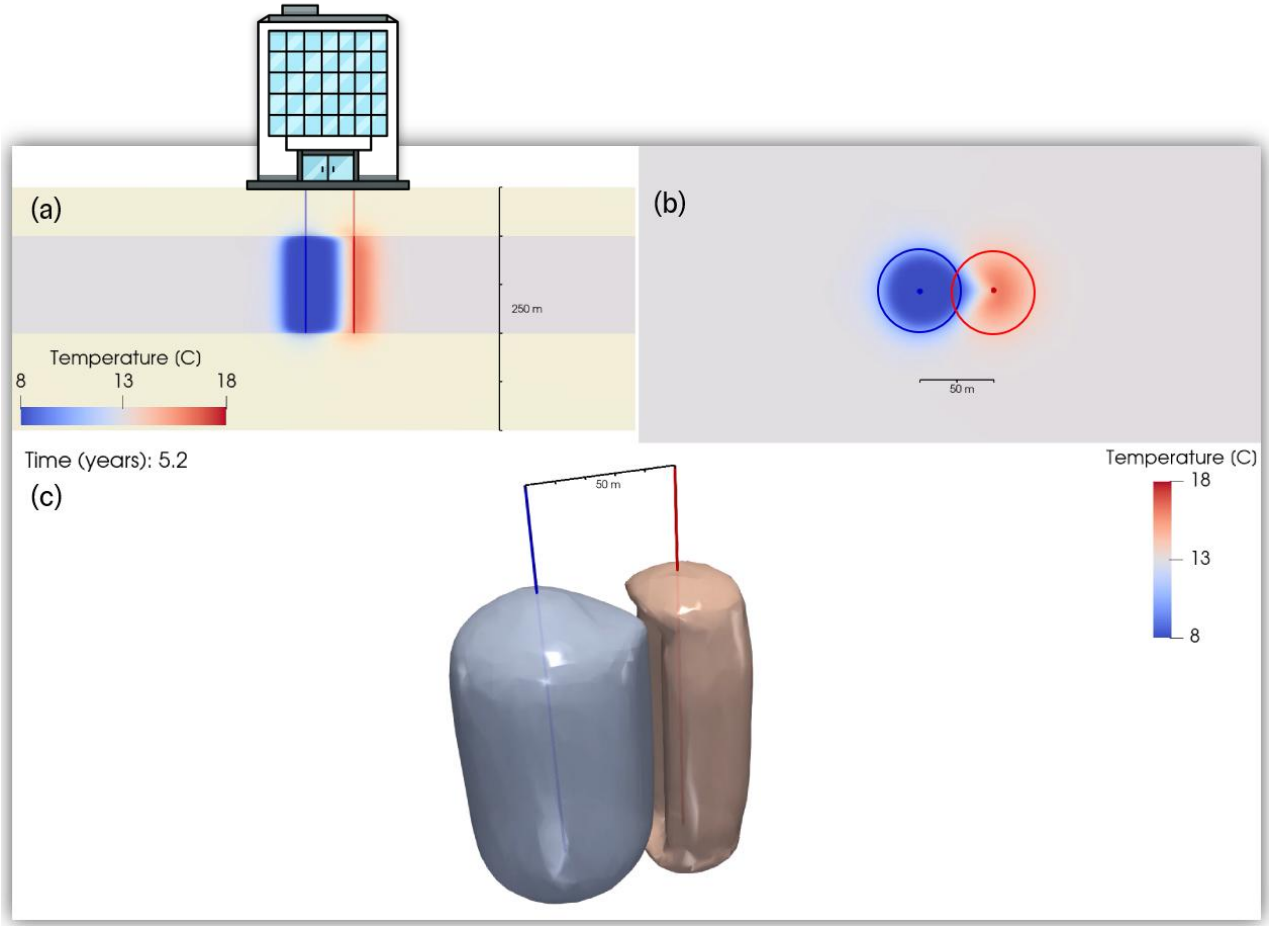


Figure 2: Snapshot after 5.2 years of operation of the thermal plumes in the optimal ATES case, showing (a) cross-section, (b) plan-view and (c) 3D views. Circles in (b) denote one thermal radius (R_{th} = 1), so the borehole spacing is slightly less than $2R_{th}$.

We finish by directly comparing energy produced and energy density across comparable ATES and GWHC systems. (Fig. 3). We find that, in the absence of significant groundwater flow, ATES produces up to double the energy of comparable GWHC and always produces more energy (Fig. 3a). Moreover, ATES is up to three times more energy dense than GWHC (Fig. 3b).

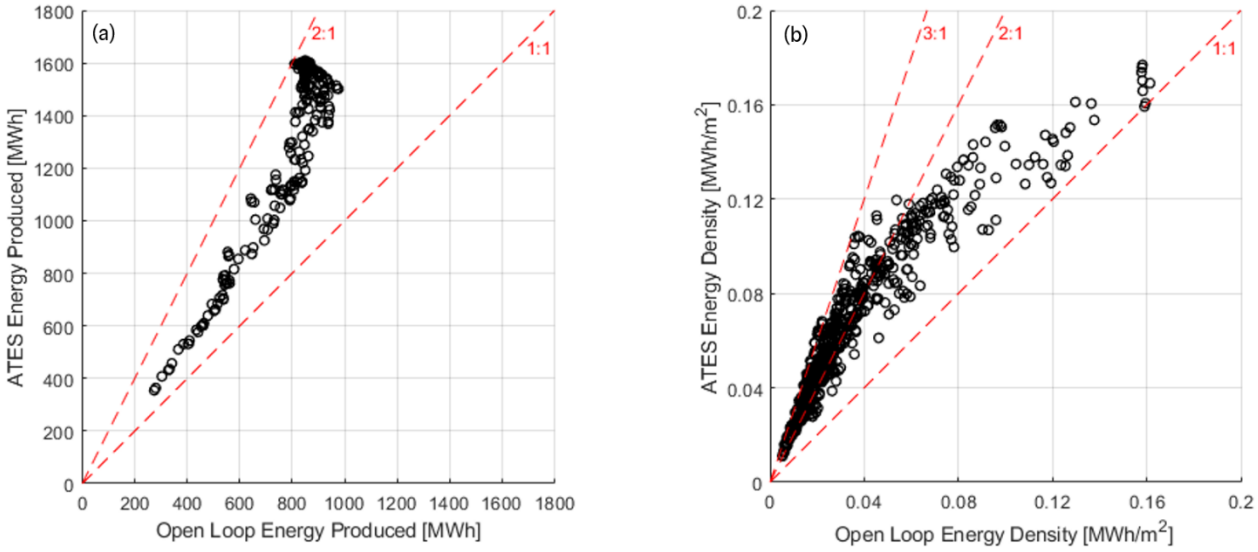


Figure 3: Cross-plots of (a) energy produced per cycle after 10 years of operation, and (b) energy density, for the equivalent GWHC (open-loop) and ATES scenarios.

CONCLUSIONS AND FUTURE WORK

ATES delivers more energy and offers higher energy density than equivalent GWHC in the absence of significant groundwater flow. Maximum energy supply is obtained with large borehole spacing to avoid thermal interference, maximizing thermal recovery as predicted in numerous previous studies. Maximum energy density is obtained with long screen length and smaller borehole spacing, which yields lower thermal recovery. Maximizing thermal recovery may not be the optimal strategy in urban deployments with high demand density.

Future studies will include heterogeneity in the aquifer models and investigate the impact of groundwater flow. We will also determine the temperature of the produced water, and its impact on heat pump efficiency and electricity consumption.

Acknowledgements

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