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**Investigating mixed-circuit injection-extraction strategies between borehole heat exchangers in a cooling dominated system**

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### Indicative summary

The project investigated an innovative approach to meeting high cooling and heating demands using mixed-circuit borehole heat exchanger (BHE) arrays, ideal for applications with continuous cooling loads, such as data centres. Currently, data centres rely heavily on grid electricity, with excess heat often wasted. The proposed system uses a network of closed-loop BHEs in which fluid circulates, transferring heat via conduction through the borehole wall. A mixed-circuit array can store excess heat in one BHE circuit while extracting heat from another, enabling the system to deliver cooling and heating simultaneously. This setup allows for passive cooling and direct heating without the need for additional heat pump systems, reducing both energy use and associated operational costs.

The project used a dual approach, involving site investigation and numerical modelling. A test was undertaken at the UK Geenergy Observatory in Cheshire using the 100 m deep BHEs in a mixed circuit experiment. Fluid was circulated at constant inlet temperatures of 1 and 30 °C for 2 heat extraction BHEs and 2 heat injection BHEs, respectively, for 90 hours to operate within the typical range of a thermal response test. This constitutes a novel thermal performance test which allows the determination of i) the effective thermal conductivity of the ground (an essential parameter in modelling closed-loop systems), ii) the estimated thermal capacity of the system, and iii) raw data that can then be used to develop numerical models capable of investigating large mixed circuit arrays. The testing determined effective thermal conductivities of 2.43 – 3.65 W/mK, with the lower value associated to heat extraction tests and the higher values to the heat injection tests. Further information can be found in detail in Brown et al. (2026).

Subsequent numerical modelling of larger scaled arrays was undertaken using OpenGeoSys software with system parameters from the UK Geenergy Observatory in Cheshire. OpenGeoSys is an open-source finite-element code that uses the dual-continuum method to model BHEs. This assumes the BHE to be a series of 1D elements, whilst the surrounding rock mass is modelled in 3D. Numerical modelling results showed that the geometrical design of the array and system controls can both impact performance in allowing sustained cooling and heating loads to be met.

## Scope and Objectives

The decarbonisation of the heating and cooling sector in the UK and internationally is critical to achieving net-zero carbon targets, while also enhancing energy security and reducing peak electricity demand on the National Grid. As cooling demand continues to rise due to climate change and urbanisation, there is an increasing need for low-carbon solutions that can provide cooling while minimising electrical consumption and making effective use of subsurface thermal resources.

The overarching aim of this project was to investigate the subsurface thermal potential of BHEs for meeting cooling demands, with particular emphasis on the feasibility of passive cooling and the associated opportunity for direct heating through thermal recovery. The project sought to improve understanding of how mixed heating and cooling loads interact within the subsurface and how these interactions can be optimised to support efficient, low-carbon energy systems.

This aim was addressed through three main objectives:

- i) conducting controlled heating and cooling trials at the Cheshire Geoenergy Observatory to characterise subsurface thermal behaviour and interactions under realistic operating conditions;
- ii) validating and testing numerical modelling approaches using the experimental data to ensure robust representation of subsurface heat transport processes; and
- iii) upscaling the validated models to investigate larger BHE arrays, enabling assessment of how combined heating and cooling loads could be implemented and managed at a system scale through numerical simulation.

Together, these activities provide a framework for assessing the role of BHE-based systems in delivering low-carbon cooling and complementary heating, supporting their integration into future energy strategies.

## Methodology

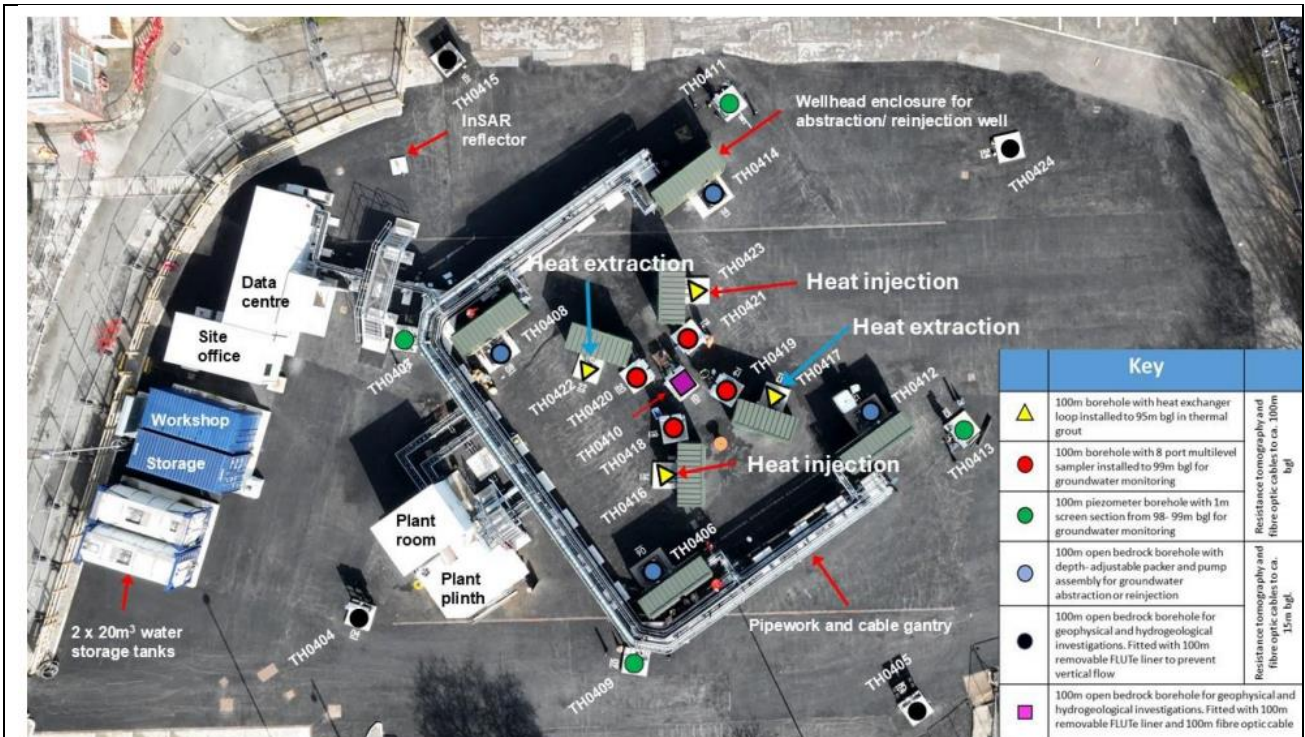
### 1. Subsurface testing using the Cheshire Geoenergy Observatory

The experiment was undertaken at the UK Geoenergy Observatory in Cheshire (Figure 1), a research site equipped with instrumentation for open- and closed-loop geothermal testing. The site

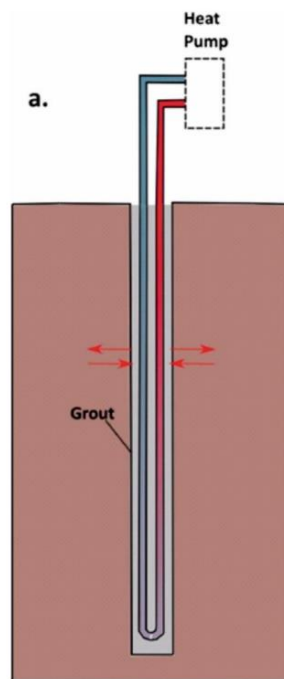
is located on the northwest boarder of the Cheshire Basin, which has high quality Permo-Triassic aquifers and a strong geothermal potential (see Plant et al., 1999; Brown, 2023 and references therein). The site includes 21 vertical boreholes drilled to a depth of 100 m, four of which were equipped with 40 mm outer diameter high-density polyethylene U-tube BHEs (Figure 2). These boreholes penetrate the Chester Formation of the Sherwood Sandstone Group, with bedrock exposed at the surface and overlain by a thin layer of anthropogenic material of less than 2 m thickness. The experiment made use of existing site infrastructure to investigate simultaneous heat injection and heat extraction under controlled operating conditions.

Thermal performance tests were conducted for 90 hours (see Brown et al., 2026), which is the typical range for such a test, using a 16-kW chiller and a 24-kW heater connected to separate hydraulic circuits, enabling concurrent operation of heated and cooled BHEs. Two boreholes were operated in heat extraction mode with a nominal inlet temperature set point of 1 °C, while two boreholes were operated in heat injection mode with a set point of 30 °C. For the heat extraction circuit, temperature control was applied at the buffer tank rather than directly at the borehole wellhead, resulting in measured inlet temperatures at the borehole head of approximately 2 °C, likely due to heat gains from surface pipework and circulation pumps. Heat injection and extraction were applied continuously during the tests, with flow rates maintained at 0.5 L/s. The heat extraction set point was chosen as 1 °C to ensure the ground did not approach freezing conditions around the infrastructure, whilst 30 °C was chosen as a likely heat rejection temperature. The flow rate of 0.5 L/s was used to ensure the flow conditions were turbulent.

Thermal performance test data were analysed to estimate effective in-situ thermal properties of the subsurface under controlled inlet temperature conditions. Previous work by Aydin et al. (2019) demonstrated that thermal performance tests conducted with fixed inlet temperatures can be used to estimate effective thermal conductivity by analysing the reciprocal of the radial heat transfer per unit borehole depth. Following this approach, temperature and flow rate measurements recorded during both heat injection and heat extraction phases were used to calculate heat transfer rates and infer effective thermal conductivity values representative of site conditions. These estimates were subsequently used for numerical modelling and interpretation of the subsurface thermal response.



**Figure 1.** Aerial photo of the Cheshire Observatory. Note the yellow triangles are the BHEs used in the experimental set up. BGS © UKRI.



**Figure 2.** Schematic of a U-tube BHEs (modified from Brown et al., 2024a).

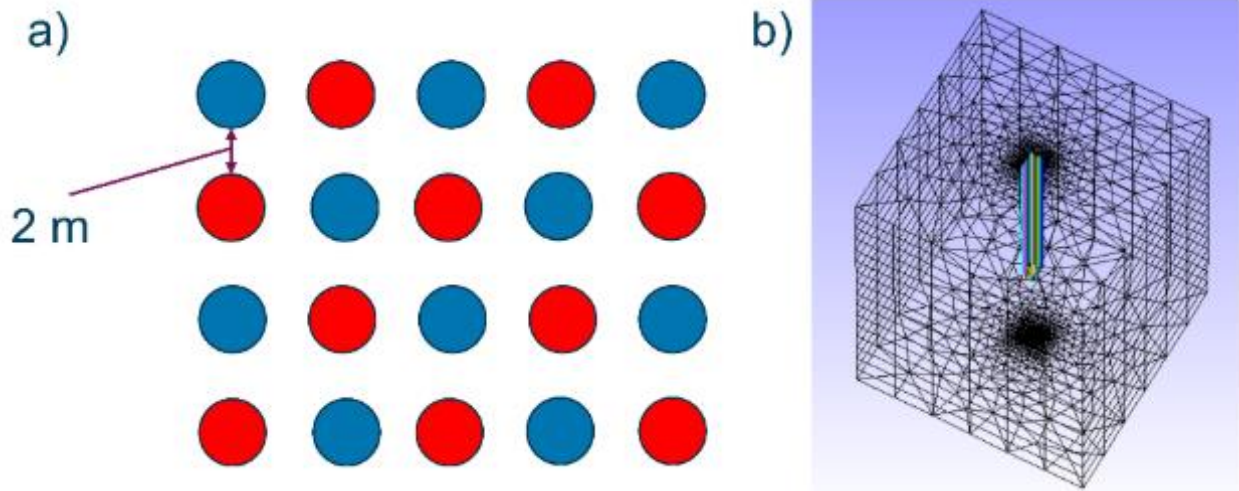
## 2. Model validation in OpenGeoSys

Effective thermal conductivity values derived from the thermal performance tests were used in forward numerical modelling to assess model suitability and evaluate how representative the calculated parameters were of the observed system behaviour. A three-dimensional rock domain of 400 m × 400 m × 200 m was defined, with a single 100 m deep BHEs positioned at its centre, ensuring sufficient separation from lateral and basal boundaries to avoid artificial thermal interactions. Owing to the large borehole spacing at the site (approximately 8.5 m), thermal interference between boreholes was negligible, allowing each borehole to be modelled independently; this was confirmed by the absence of temperature changes in nearby non-operational boreholes during the tests. Initial conditions were prescribed using a constant average undisturbed ground temperature, assuming thermal equilibrium between the borehole components and the surrounding ground, and modelled temperature responses were compared directly with measured test data to validate the numerical approach.

## 3. Numerical modelling of large arrays in OpenGeoSys

An array of twenty boreholes was simulated as a hypothetical scenario for a typical medium sized system, comprising of ten extraction boreholes and ten storage boreholes, each 100 m deep (Figure 3a). A finite element model was developed using the BHE module implemented in OpenGeoSys (e.g., Kolditz et al., 2012; Shao et al., 2016). This module employs a dual-continuum approach, in which the BHE is represented as a line element embedded within a three-dimensional rock domain (Figure 3b), allowing for efficient coupling between fluid flow in the boreholes and heat transport in the surrounding ground. The meshed domain was 120 m × 120 m × 160 m (x, y, z) for the base case, with the mesh extended for deeper borehole models undertaken during parametric studies. Boundary and initial conditions are as described for the validation.

During operation conditions for the base case, a constant inlet fluid temperature of 15 °C was prescribed, whereas a higher inlet temperature of 30 °C was applied for storage operation. Both storage inlet temperature and extraction inlet temperatures were implemented in alternating BHEs to test the concept of mixed extraction-injection strategies. A series of simulations was conducted to investigate the effects of different system configurations (see figure 3 and 4), including variations in borehole depth (50 to 300 m), borehole spacing (2 to 8 m spacing), and operational modes (i.e., varied inlet temperatures between 5 and 50 °C). All material and thermal parameters were adopted from the Cheshire site test characterisation to ensure that the simulations accurately reflect site-specific geological and thermal conditions, thus upscaling test results (see table 1).



**Figure 3.** a) Alternating configuration for injection (red) and extraction (blue) of heat/coolth, and b) example mesh for the base case. © 2026 University of Glasgow

**Table 1.** Base case parameters for the simulations.

Parameter	Value	Units
Each borehole diameter	0.152	m
Each borehole length	100	m
Pipe inner diameter	0.0326	m
Pipe thickness	0.0037	m
Pipe thermal conductivity	0.39	W/(m·K)
Ground thermal conductivity	3.65	W/(m·K)
Ground volumetric heat capacity	$1.824 \times 10^6$	J/(K·m <sup>3</sup> )
Fluid flow rate per borehole	0.0005	m <sup>3</sup> /s
Fluid density	1039	kg/m <sup>3</sup>
Fluid volumetric heat capacity	$3.953 \times 10^6$	J/(K m <sup>3</sup> )
Fluid thermal conductivity	0.6	W/(m·K)
Dynamic fluid viscosity	$8 \times 10^{-4}$	kg/(m·s)
Initial rock temperature	12.1	°C
Surface temperature	9.8	°C
Grout thermal conductivity	2.0	W/(m·K)
Grout volumetric heat capacity	$1.485 \times 10^6$	J/(K m <sup>3</sup> )

### Stakeholder Engagement

As part of the project there has been liaison with our industry partner from TownRock Energy who has worked on a range of operational geothermal projects and underground thermal energy storage systems. Notably with focus on the BODYHEAT project which captures, stores and reuses waste

heat using thermal energy storage in a series of BHEs in Glasgow (Brown et al., 2024b). Furthermore, stakeholder engagement has also been undertaken at REEF-UKC project meetings, and conferences – including the European Geoscience Union, the 12<sup>th</sup> Geothermal Symposium and the 18th International Conference on Sustainable Energy & Environmental Protection. Formal presentations were given at all (see project outputs), and meetings were had throughout. This directly fed into modelling assumptions, control strategies, geometrical design of the system and the subsurface testing regimes.

### Risks & Mitigations

The key risks associated with the project related to the use of the Geoenergy Observatory in Cheshire. These included potential technical issues with the testing facility, such as pump failure or heater/chiller malfunction, as well as time constraints arising from limited facility availability and the possibility of overlapping bookings by other users.

These risks were mitigated in collaboration with the observatory's operational team through the development of detailed risk assessments and method statements, ensuring that all experimental procedures were clearly defined and safely managed. Test runs were conducted in advance of the main experiment to verify system performance, identify potential faults, and ensure the smooth operation of equipment.

In addition, several contingency dates were scheduled to accommodate unforeseen technical issues or changes in observatory availability. This approach reduced the likelihood of significant delays and ensured that the experimental programme could be completed successfully within the project timeframe.

### ECR Involvement

Several early career researchers (ECRs) played central roles in the delivery of this project, contributing both to its scientific development and to their own professional progression. These included:

- **Christopher S. Brown** (formerly University of Glasgow; now British Geological Survey)

- **Isa Kolo** (University of Glasgow)
- **Sean M. Watson** (formerly TownRock Energy; now University of Glasgow)

The ECRs were actively involved from the outset of the project, contributing to the design of the research programme, the development of experimental methodologies, and the overall workflow. Rather than being limited to supporting roles, they were given responsibility for leading specific work packages, ensuring hands-on experience in planning, execution, and interpretation of results. This approach enabled the ECRs to develop practical skills in experimental design, field-based research at a national facility, numerical modelling, and data analysis, as well as broader project management and coordination skills. Their involvement also included engagement with facility operators and external partners, strengthening their experience of collaborative research environments. Overall, the project provided meaningful leadership and training opportunities, supporting the professional development of early career researchers in subsurface energy and geoenery research.

### **Project Outcome**

#### **Site investigation at the UK Geoenery Observatory in Cheshire:**

This study documented what was believed to be one of the first thermal performance tests (TPTs) conducted in a UK setting, incorporating both heat injection and heat extraction modes (Brown et al., 2026). The tests demonstrated that TPTs could be used effectively to characterise in-situ ground thermal properties, yielding effective thermal conductivity values in the range of 2.43–3.65 W/mK, which were consistent with values obtained from laboratory measurements on core samples (see TH0424 final data pack - Contains NERC materials ©NERC 2024 (UKGEOS Cheshire Project Team, 2023)). In addition, the tests highlighted the potential dual role of TPTs: not only for determining subsurface thermal parameters, but also for estimating the operational thermal capacity of ground source heat pump (GSHP) systems for both cooling applications (via heat rejection) and subsurface thermal energy storage. Measured specific heat extraction rates of approximately 38–40 W/m and heat injection rates of approximately 69–73 W/m indicated the relevance of TPTs for assessing system longevity, extraction performance, cooling performance, and the feasibility of borehole thermal energy storage.

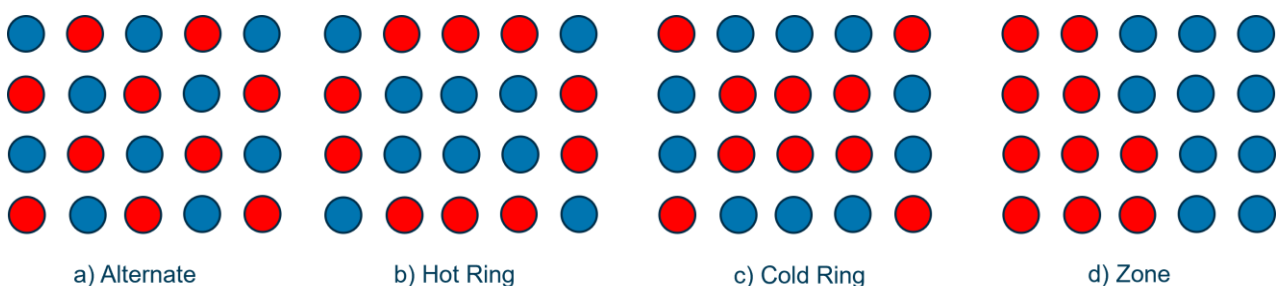
#### **Model validation and interpretation of results**

The effective thermal conductivity values derived from the TPTs were evaluated using forward modelling in OpenGeoSys, with simulated temperatures typically matching measured data to within

<1 °C over the duration of each test. While good agreement was achieved overall, heat extraction TPTs showed an apparent underestimation of thermal conductivity. Through parameterisation and testing in OpenGeoSys, this discrepancy was attributed either to operational noise caused by chiller cycling around the target inlet temperature, which introduced temperature fluctuations of approximately 1.5 °C, property variations input into the numerical model (i.e., discrepancy in measured flow rate/grout thermal conductivity versus the input into OpenGeoSys), or to physical processes such as natural groundwater convection enhancing apparent thermal conductivity during heat injection. Groundwater convection was particularly relevant given that the Sherwood Sandstone Group was a known water-bearing aquifer. The findings emphasised both the importance of careful experimental control and the value of numerical modelling for interpreting TPT data and validating parameter estimates.

### Numerical modelling in OpenGeoSys:

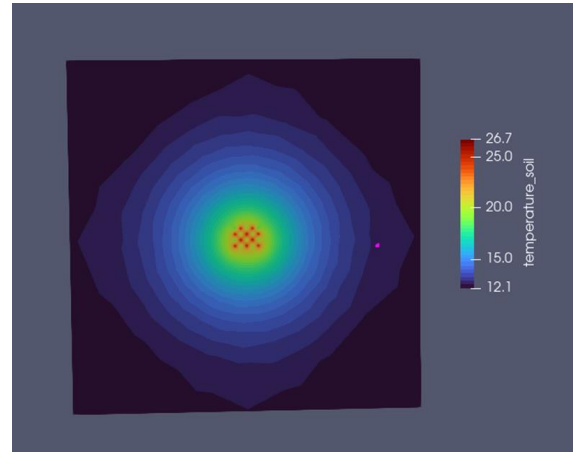
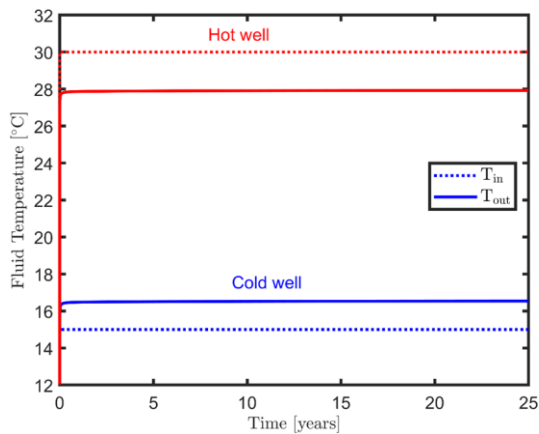
Following the validation of the experiments conducted at the Cheshire Observatory, numerical modelling was undertaken to test larger scaled solutions for different array designs. Simulations showed the potential of a mixed-circuit array to simultaneously fulfil heating and cooling demand. The base case had alternate boreholes as shown in Figure 4a. The figures show red boreholes which inject heat to meet cooling demand and blue boreholes which extract heat to meet heating demand. In the injection boreholes, 4.15 kW was available as a cooling load per borehole; and for the extraction boreholes 2.95 kW was extracted per borehole. The average fluid temperatures in hot and cold boreholes are shown in Figure 5a. Figure 5b shows the contours of the rock temperature after one year. Other geometrical configurations of BHE array considered are shown in Figures 4 (b) - (d).



**Figure 4.** Different configurations of injection (red) and extraction (blues) boreholes considered. © 2026 University of Glasgow

Out of the four configurations considered for the mixed array, the alternate configuration injected the most amount of heat ~4.15 kW per borehole, supplying the greatest cooling load. The hot ring

configuration extracted the most amount of heat  $\sim 7.71$  kW per borehole. The zone configuration injected and extracted the least amount of heat. It is also noted that the zone configuration has the least interaction between injection and extraction boreholes.



a) Average fluid temperatures over 25 years period. Red for injection and blue for extraction borehole. Inlet temperature is dotted line and outlet temperature is solid line.

b) Contours of rock temperature at 1 year (in °C)

**Figure 5.** Fluid and rock temperatures from 20-borehole array. © 2026 University of Glasgow

In addition to the base case with continuous operation of both the injection and extraction boreholes, two intermittent modes of operation were considered: (a) injection boreholes were in continuous operation throughout the year but extraction boreholes were only operational for the first 6 months of the annual cycle; (b) injection boreholes were in operation only for the first 6 months, the extraction well starts with extraction for the first 6 months and then switches to injection in subsequent 6 months. Hence, both modes of operation were designed to have continuous heat supply. Results did not vary significantly between the base case and the intermittent modes of operation considered. While the average rock temperature reduces with increased spacing, it reduces the heat extraction potential of the boreholes. Heat injection did not show significant variation with different borehole spacings considered. With deeper boreholes, more heat can be extracted, and more heat can be injected. Deeper boreholes provide a greater area for heat exchange and hence the specific heat extraction/injection reduces as the depth increases.

With careful design these systems are likely to be able to support both direct heating and passive cooling loads. Future work will investigate further and identify the differences in performance when using with and without heat pumps, with integrated varied load for heating and cooling.

## Project outputs

The project had several outputs including publications and presentations. These include:

### **1. Paper in the final stages of peer review:**

Brown, C.S., Kolo, I., Falcone, G., Friedrich, D. and Watson, S.M., 2026. Thermal Performance Testing of Shallow Geothermal Systems: Insights from Field Experiments and Numerical Modelling. *Geothermics*.

### **2. Presentation at European Geoscience Union, Vienna, April 2025:**

Brown, C.S, Kolo, I., Falcone, G., Friedrich, D. and Watson, S., 2025. Investigating mixed-circuit injection-extraction strategies between borehole heat exchangers in a cooling dominated system. European Geoscience Union. <https://doi.org/10.5194/egusphere-egu25-3141>

### **3. Presentation to 18th International Conference on Sustainable Energy & Environmental Protection (SEEP), July 2025:**

Kolo, I., Brown, C.S, Falcone, G., Friedrich, D. and Watson, S., 2025. Mixed-Circuit Injection-Extraction Strategies for Borehole Heat Exchangers.

### **4. Presentation at the UK's 12th Geothermal Symposium, November 2025:**

Brown, C.S, Kolo, I., Falcone, G., Friedrich, D. and Watson, S., 2025. Investigating mixed circuit borehole heat exchangers for thermal energy storage and extraction. 12<sup>th</sup> Geothermal Symposium. <https://www.geolsoc.org.uk/media/z1mbsq/abstract-book-2025-geothermal.pdf>

### **5. Presentation for REEF-UKC webinar, November 2025.**

Brown, C.S, Kolo, I., Falcone, G., Friedrich, D. and Watson, S., 2025. Exploring the UK Geenergy Observatory in Cheshire: Applications for Heating and Cooling.

### **6. A paper is being finalised on the numerical modelling of aspects of the study.**

Kolo, I., Brown, C.S, Falcone, G., Friedrich, D. and Watson, S., (in preparation). Mixed-Circuit Injection-Extraction Strategies for Borehole Heat Exchangers.

## Project Impacts and their realisation

### Technical impact during ground investigation:

The project demonstrated the practical use of thermal performance tests (TPTs) in a UK sandstone setting to characterise in-situ ground thermal properties for both heat extraction and heat injection. High-resolution measurements of temperature and flow during the experiments enabled reliable estimation of effective thermal conductivity and heat transfer rates under controlled conditions. This work de-risks the deployment of BHE systems by providing validated field data on subsurface behaviour, improving confidence in design parameters for both cooling and heating applications, as well as for borehole thermal energy storage systems (e.g., Desguers et al., 2025). Additionally, the dataset establishes a reference for future UK-based TPTs, helping to standardise experimental protocols and supporting wider uptake of subsurface thermal energy technologies.

### Technical impact during numerical modelling of cooling (and heating) systems of the subsurface:

The derived thermal properties were integrated into forward numerical models using OpenGeoSys to simulate BHE performance in both heating and cooling modes. The models reproduced observed temperature responses to within 1 °C, validating the suitability of the effective thermal conductivity estimates and confirming the reliability of the modelling approach. This capability provides a robust framework for predictive design of BHE systems, allowing engineers and researchers to explore system performance under different borehole configurations, spacing, and operational scenarios before field deployment. The approach also facilitates evaluation of energy storage potential and optimisation of long-term system efficiency.

### Environmental impact:

By characterising subsurface thermal properties and validating numerical models for heating and cooling, the project supports the use of passive cooling and direct heating via BHEs. These strategies reduce dependence on electrically driven systems, including heat pumps, thereby reducing peak electricity demand, lowering carbon emissions, and enhancing energy security. This reduces the pressure on the National Grid. Improved understanding of ground thermal behaviour also enables more efficient and reliable design of BHE systems, facilitating sustainable integration of seasonal subsurface energy storage and contributing to decarbonisation of the built environment.

### Next Steps and outlook

The project has successfully demonstrated new methods of site investigation and possibility to use mixed load methods with a BHE array. However, it has also led to further research aspirations, including:

1. Evaluate further methods of testing closed loop cooling dominated systems.
2. Investigate real world loads incorporated into the system.
3. Optimisation of the array.
4. Upscaled temperatures through heat pump incorporation.

### Acknowledgements

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