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Modelling Unconventional Geothermal Resource Exploitation in the UK: Impacts from Deep Borehole Heat Exchangers and Closed-loop U-tubes

Part 1: Deep Borehole Heat Exchangers

Christopher S Brown , Isa Kolo, Hannah Doran, Theo Renaud,
Gioia Falcone, David Banks, David C.W. Sanderson

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Overview

- Location: Newcastle Science Central Deep Geothermal Borehole
- Investigating modes of operation – constant heat load v intermittent
- Super-Deep borehole heat exchanger, parametric study

Project Partners and Collaborators

Modelling Approach

Model Design and Set-up

- Transient homogenous numerical models for the Newcastle Science Central Deep Geothermal Borehole (NSCDGB) and super-deep scenario were developed on OpenGeoSys using the ‘Dual-continuum method’.
- Model a deep coaxial borehole heat exchanger, where the central pipe produces fluid (‘outlet’) and the annular space injects fluid (‘inlet’) in a closed-loop system (fig. 1).
- Previous studies working on the NSCDGB have focused on parameterisation and thermal energy storage (Kolo et al., 2022; Brown et al., 2023). The work presented here is focusing on operation and is part of a piece of work looking at modes of operation and scalability:

‘Brown, C.S., Kolo, I., Falcone, G. and Banks, D., 2023. Investigating scalability of deep borehole heat exchangers: Numerical modelling of arrays with varied modes of operation. Renewable Energy, 202, pp.442-452.’

- The extension of this to super-deep scenarios looks at a notional study after it was mentioned there are plans to look at a 6 km deep borehole in Glasgow:

City of Glasgow, Scotland explores possibility of 6,000m geothermal well (thinkgeoenergy.com)

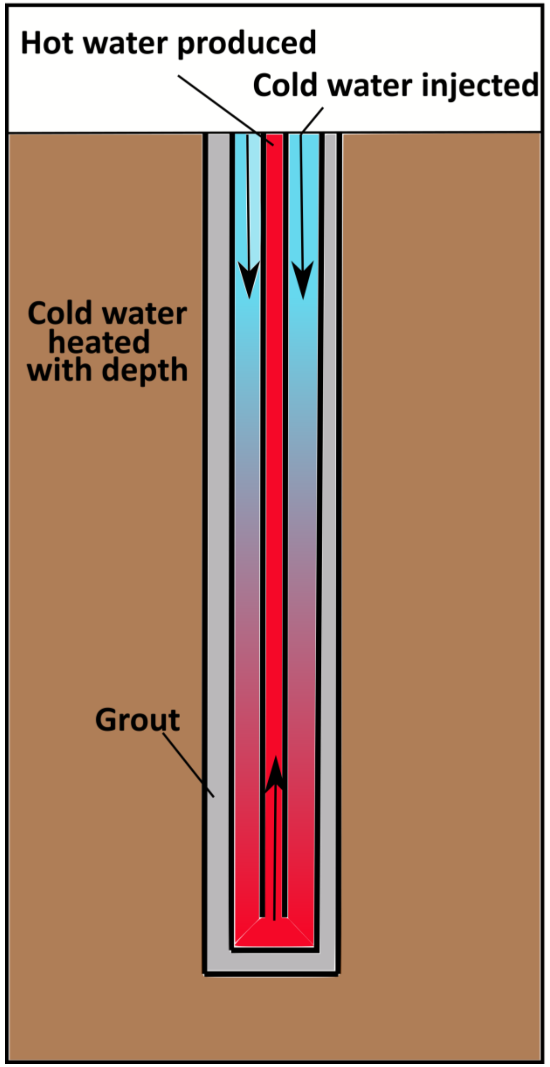

Figure 1. Closed-loop, deep, coaxial borehole heat exchanger design (after Brown et al., 2021, 2023).

Locality of the Newcastle Science Central Deep Geothermal Borehole

Introduction

- Aiming to evaluate the potential to repurpose the Newcastle Science Central Deep Geothermal Borehole (NSCDGB).
- Drilling began in 2011 to test the geothermal potential of the Fell Sandstone Formation.
- Geothermal gradient of up to 37 °C/km encountered and 376.5 m of Fell Sandstone Formation.
- Hydraulic conductivity proved to be poor and limited further development.
- Can this resource be exploited using the deep borehole heat exchanger (DBHE) design (to 920 m)?

Location

- Borehole is located to the northeast of England in Newcastle where heat flows are elevated due to the presence of the North Pennine Batholith.
- The borehole cuts a clastic and carbonate Carboniferous succession of strata.
- The Newcastle Helix borehole is located adjacent to the Urban Science Building which has >4000 sensors and could provide a proximal demand for the heat load.

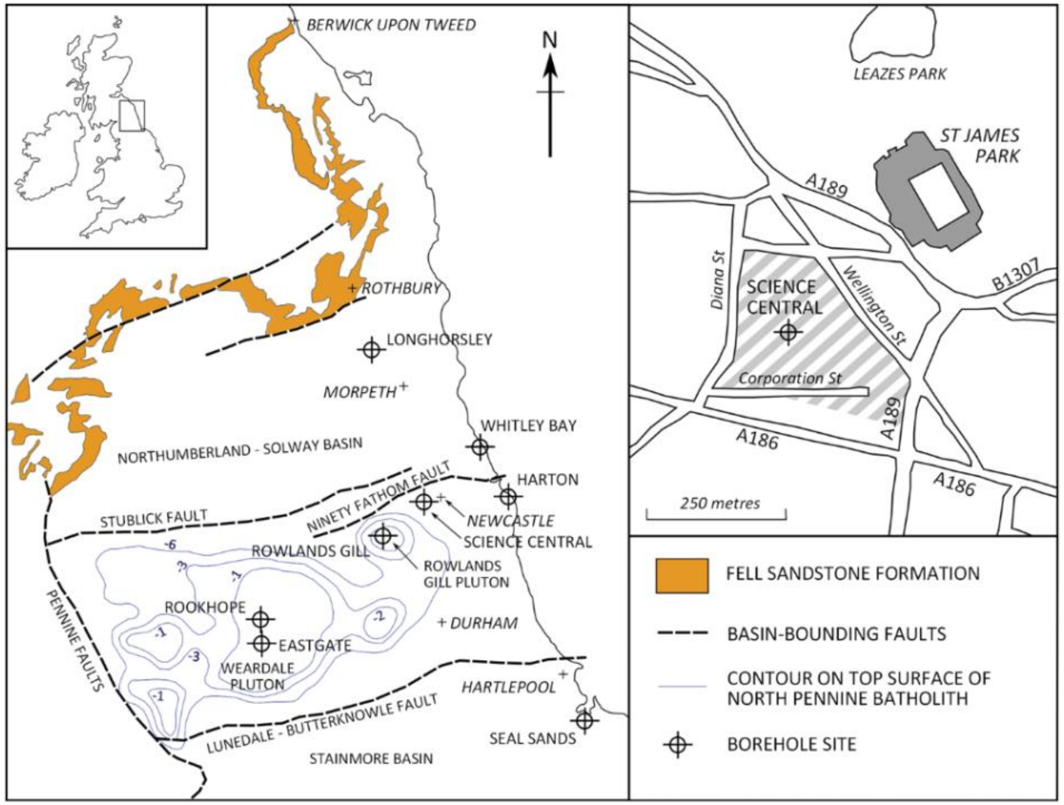

Figure 2. Locality map, highlighting the position of the Newcastle Helix in context of UK geography and nearby geology (after Younger et al., 2016).

Results NSCDGB: Investigating Modes of Operation

- Testing the influence of modes of operation on the ability of the DBHE to meet building demand in winter. Operating power of 50 kW applied.
- Intermittent operation consisted of 50 kW applied for a heating season, followed by 6 months rest.
- Higher operating temperatures for intermittent operation (but less energy extracted).
- 6 months operation can supply ~220 MWh which can supply ~285 MWh to the building after passing through a heat pump. Close to a quarter of building demand.
- Intermittent operation allows replenishment of resources, whilst the constant load results in a decline of heat extracted with time.

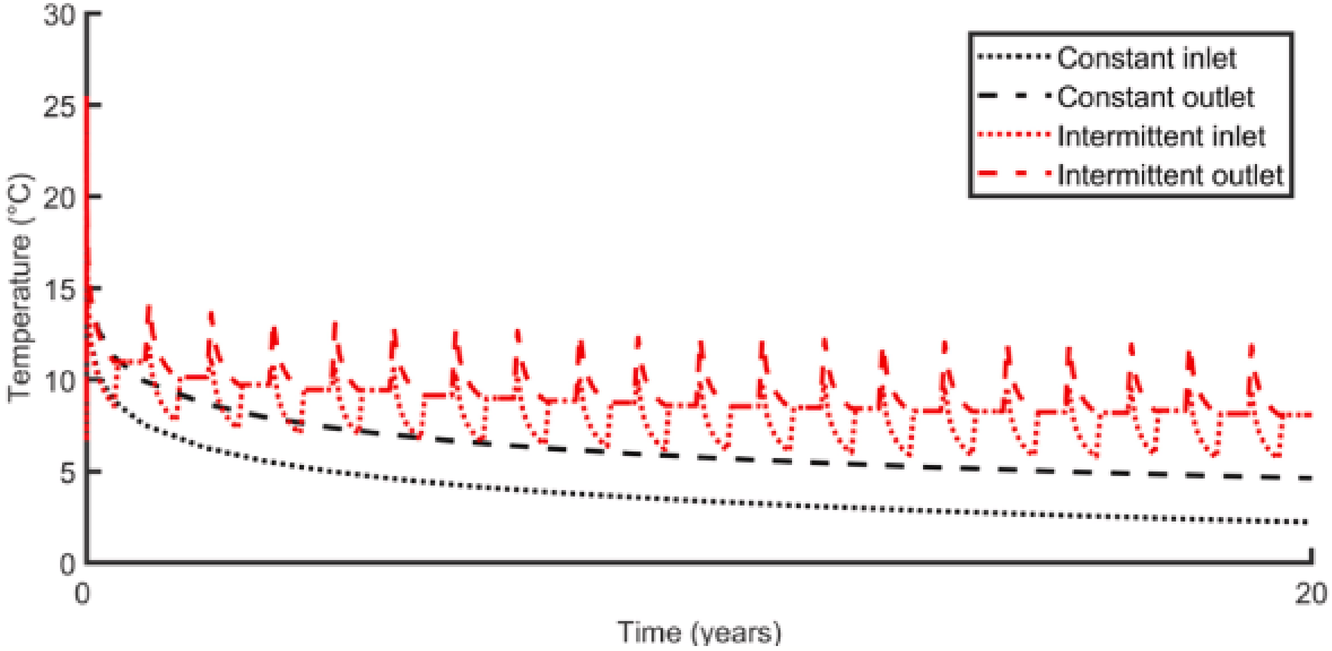

Figure 3: Intermittent v constant heat load operation for a single DBHE.

Results NSCDGB: Investigating Modes of Operation

- What happens if you extract the same amount of heat per annum?
- When applying the same total energy extracted temperature remains higher for constant heat load application (i.e., 25 kW heat load constant v 50 kW for 6 months).
- Part of a study that also investigates scalability and it was shown for this case there would need to be at least 4 boreholes at 920 m depth to supply the building demand.
- Next steps aim to model the true building load to the borehole to see how they compare.
- A thermal response test is also planned and we can then use this data to refine our models.

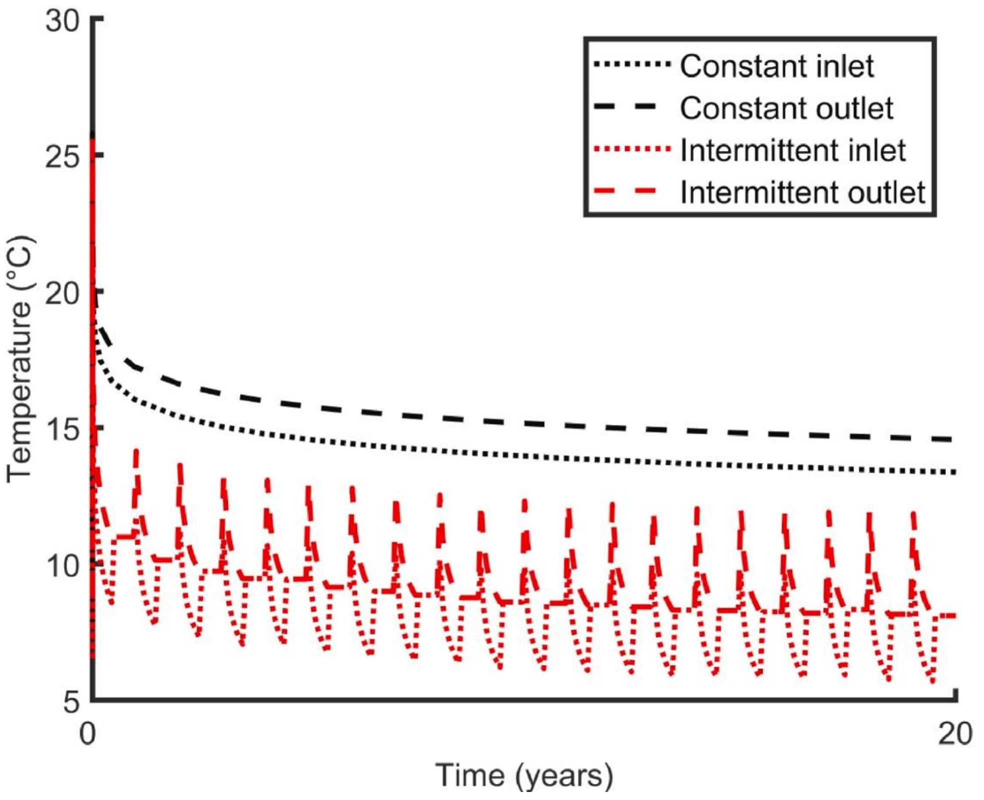

Figure 4: Intermittent (50 kW) v constant heat load (25 kW) operation for a single DBHE.

Notional 6 km DBHE: Model Set-up and Parameters

- Surface temperature of 10.17°C and a geothermal gradient of 35.92 °C/km (Paisley Coats Meteorological Office Observatory in Glasgow)
- DBHE parameters largely as discussed before with a homogeneous lithology
- Thermal conductivity of 2.55 W/(m·K) but sensitivity analysis is performed
- Water as heat transfer fluid based on efficiency (Alimonti and Soldo, 2016)
- Mass flow rate of 8.33 kg/s but sensitivity analysis is performed
- Constant load simulations and constant inlet temperature simulations for one heating season

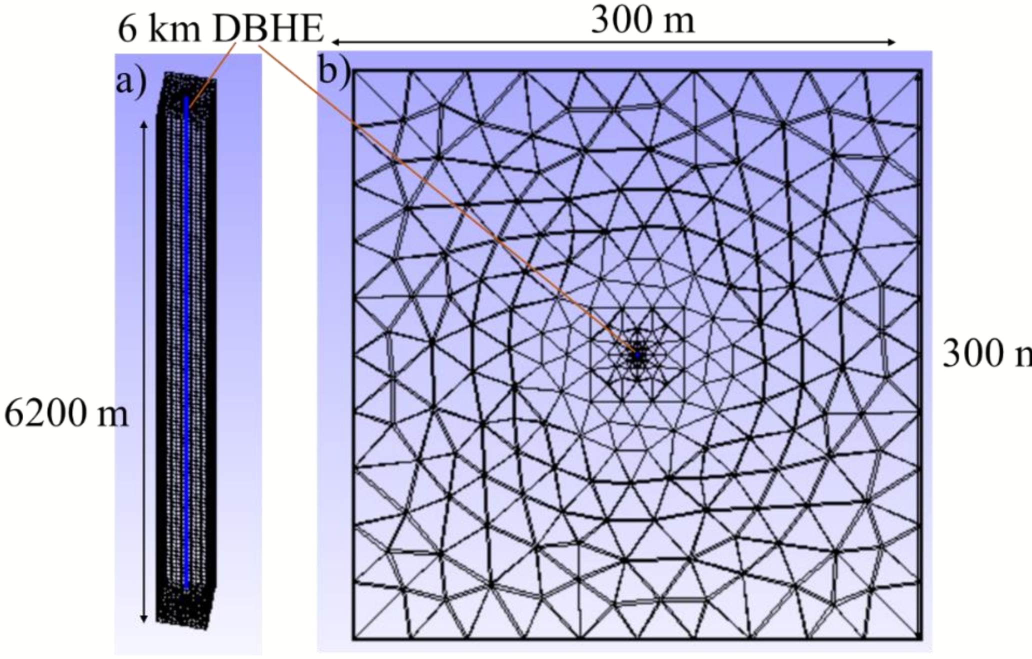

Figure 5: Geometry and mesh for notional 6 km DBHE

Results: Application of a Constant Heat Load of 800 kW

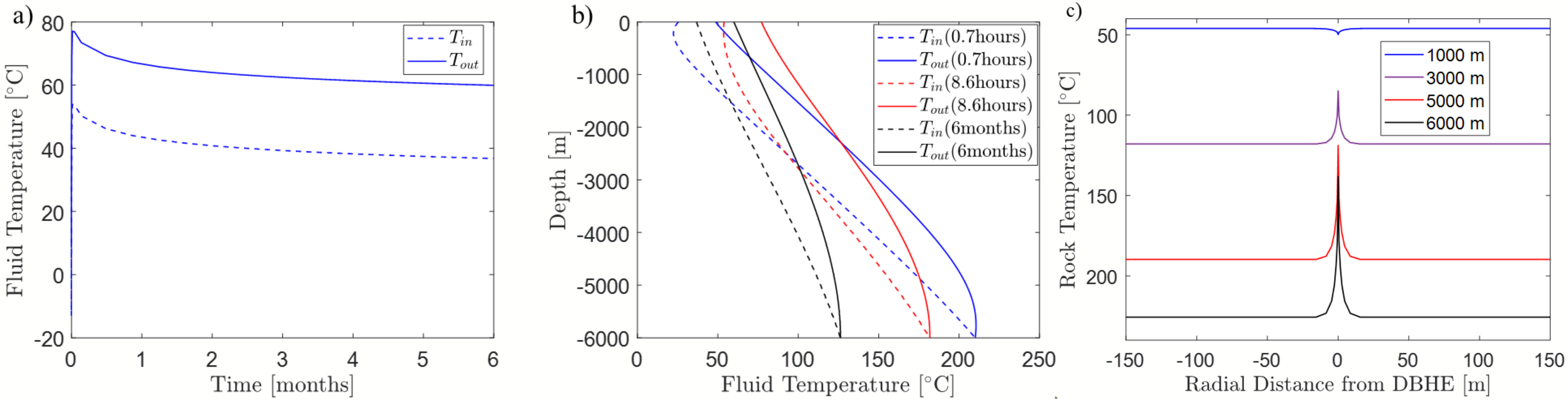

Figure 6: Inlet and outlet fluid temperatures (a,b) and rock temperature (c) for an imposed load of 800 kW at 6 months

- After 6 months, temperature reaches 60°C.
- Downhole temperatures are significantly higher but there are losses during outflow.
- While heat is being extracted from ≥ 3 km, there is heat gain in the upper part of the borehole.

Results: Varying the Heat Load Imposed

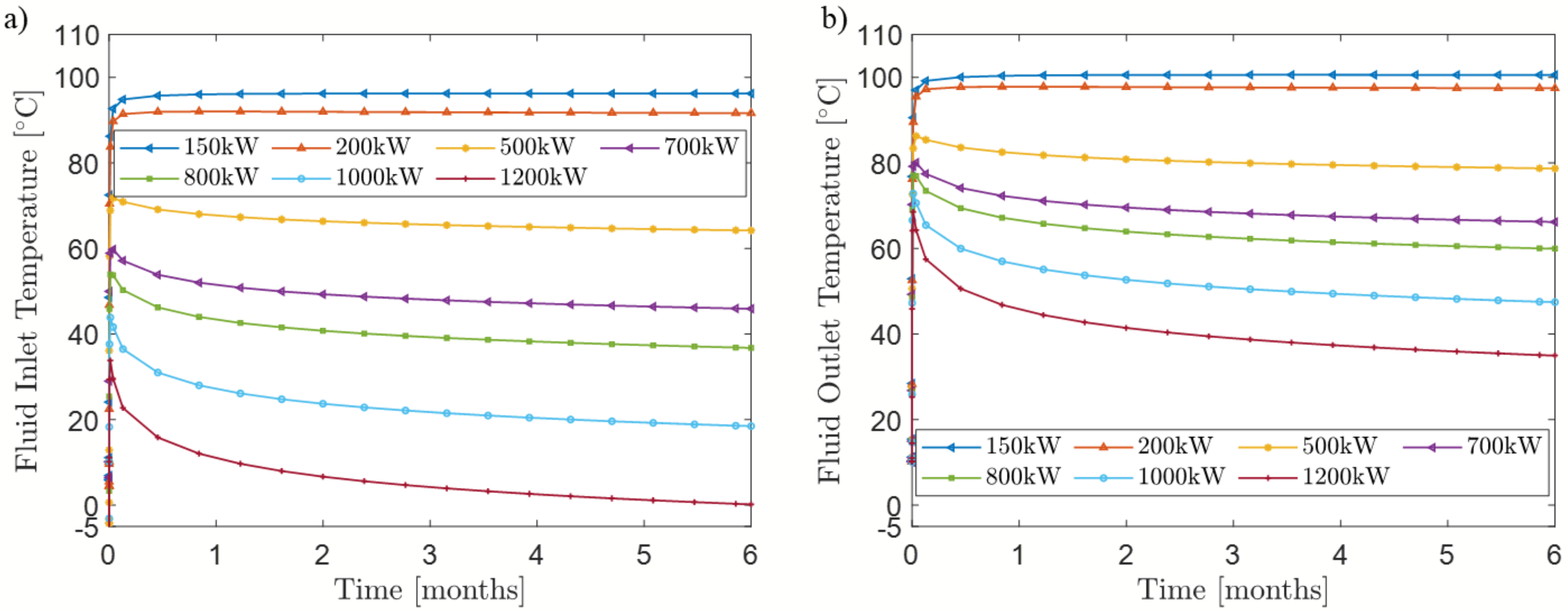

Figure 7. Inlet and outlet fluid temperatures (a,b) for different heat loads

- For a heat load of 1000 kW, the outlet temperature is 18.48°C.
- To obtain a minimum outlet temperature of 100°C, only 150 kW thermal power can be supplied.
- This increases to 500 kW if we are assuming a cut-off of 77 °C.

Table 1. inlet and outlet fluid temperatures for different heat loads at 6 months

Heat Load [kW]	150	200	500	700	800	1000	1200
Inlet Temp. [°C]	96.20	91.63	64.20	45.91	36.77	18.48	0.19
Outlet Temp. [°C]	100.55	97.43	78.69	66.19	59.95	47.45	34.96

Results: Constant Heat Load with a Varied Thermal Conductivity and Mass Flow Rate

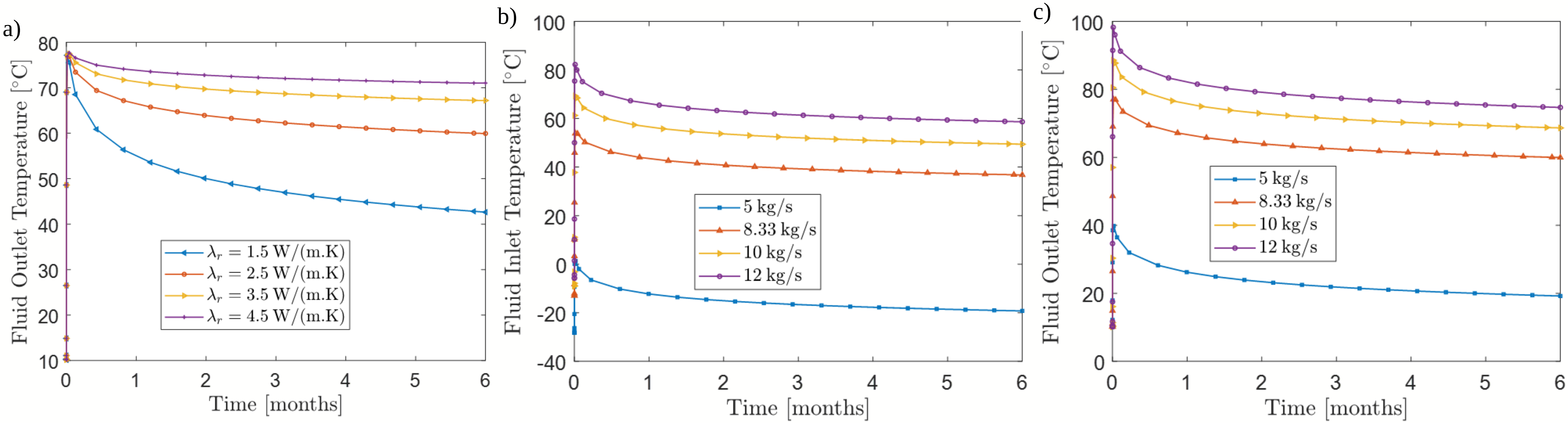

Figure 8. Outlet fluid temperatures for different thermal conductivities (a); inlet and outlet temperatures for different mass flow rates (a,b).

- There is an increase in outlet temperature with increase in thermal conductivity: 60°C for 2.5 W/(m·K) and 67°C for 3.5 W/(m·K)
- A mass flow rate of 5 kg/s results in an inlet temperature of –19°C after 6 months.

Results: Constant Inlet Temperature and Varied Mass Flow Rate

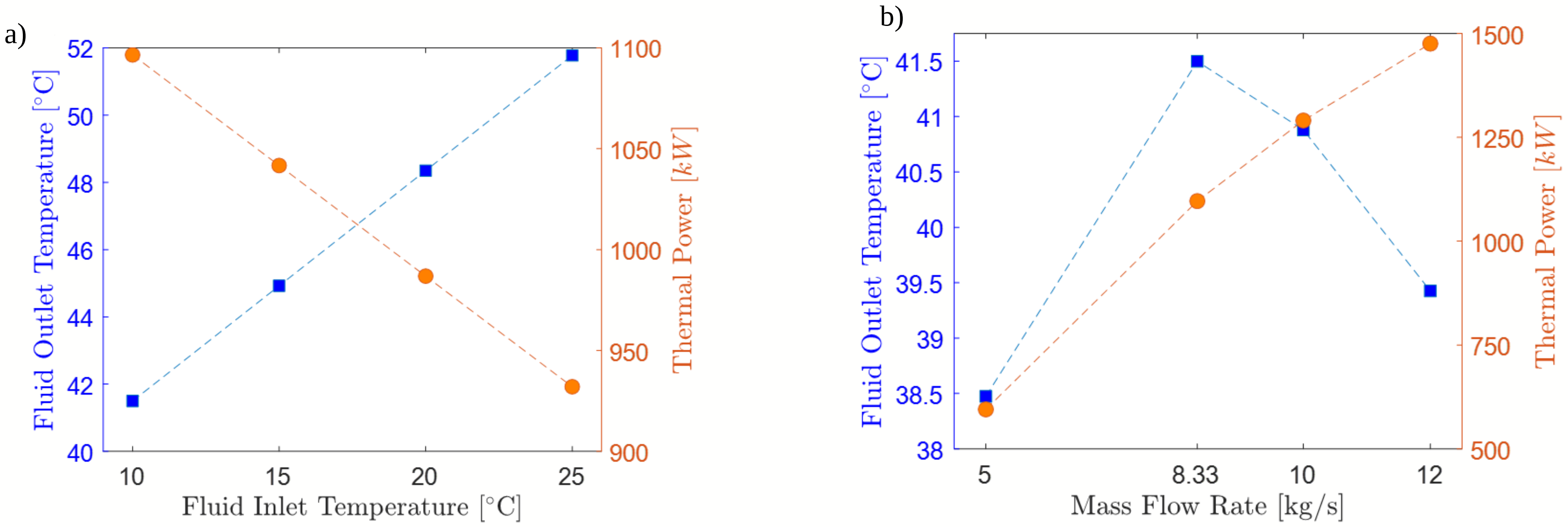

Figure 9. Outlet fluid temperatures and thermal power for varying inlet temperature (a) and varying mass flow rate (b)

- The lowest temperature 10°C gives the highest outlet temperature and thermal power (1096 kW).
- The optimum mass flow rate appears to be 8.33 kg/s.

Conclusions and Future Outlook

NSCDGB

- Intermittent heat load applied allows the replenishment of the heat in proximity to the DBHE.
- If using the same heat load then it is best to operate intermittently.
- However, if using the same energy supplied to the building it is best to operate at a constant heat load for resource longevity.

6 km deep borehole heat exchanger

- For a cut-off outlet temperature of 100°C, around 150 kW thermal power can be obtained from the DBHE
- This will increase with a higher thermal conductivity of the rock.
- Insulating the top part of the DBHE is likely to improve performance
- Most geothermal power plants have installed capacities ≥ 1 MW electricity which cannot be supplied by a very deep DBHE despite the huge cost of drilling to 6 km
- The output from the DBHE appears to be not economically viable and conventional DBHE seem to be best suited for space heating.

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Part 2: Modelling unconventional geothermal resource exploitation in the UK

Decay heat potential from radioactive waste in a geological disposal facility using closed-loop U-tubes

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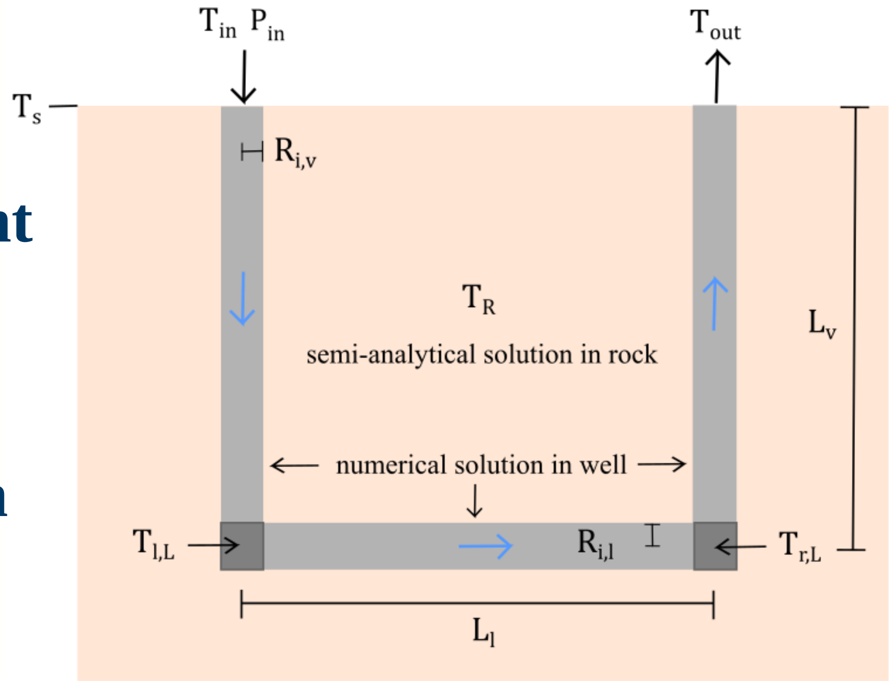
Co-generation waste heat recovery

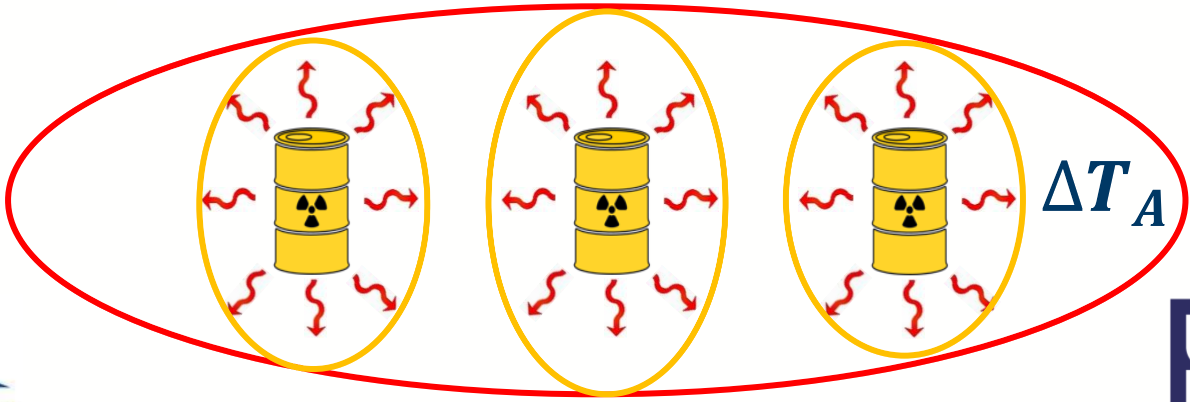
Natural geothermal gradient

$$T_R = T_S + (G \times L_v)$$

Anthropogenic heat addition

$$T_R = T_S + (G \times L_v) + \Delta T_A$$





Model assumptions:

- T2Well-EOS1/TOUGH2 (full U-tube) and T2Well-ECO2N/TOUGH2 (lateral only).
- Conduction only in rock.
- Single phase flow.

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Heat Source Term Only

- Inventory and decay heat C++ code for spent nuclear fuel (Doran et al 2022a).
- Generic high-heat producing waste (HHPW) canister decay heat vs cooling time curve (Jackson et al 2016).
- Three host rocks: evaporite (EV), higher-strength rock (HSR) and lower-strength sedimentary rock (LSSR).
- LSSR after 10 years revealed highest temperature gradient → lowest thermal diffusivity → higher peak temperatures at source = safety concerns (Doran et al 2022b).

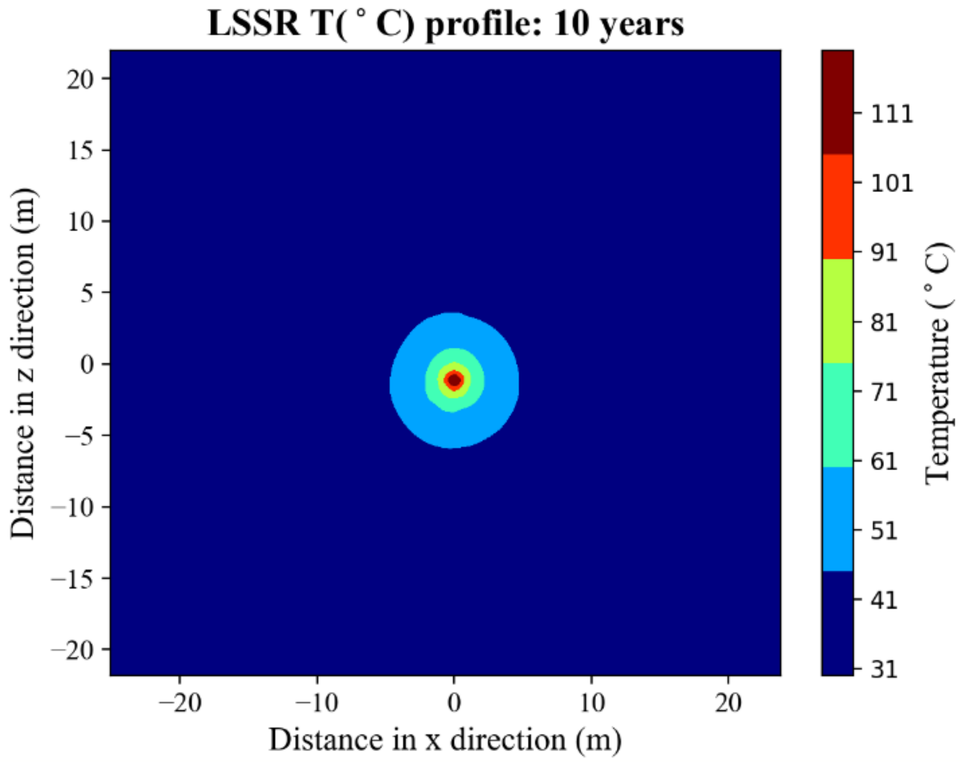

Figure 2. Temperature profile in LSSR after 10 year thermal spread.

Closed-loop geothermal system (CLGS) only

- First study: preliminary ‘Eavor-like’ U-tube CLGS assessments in same 3 host rocks, at vertical depths 1 km, 3 km and 5 km for 1 year simulations (Doran et al 2022c).
- Semi-analytical solution in rock and full numerical solution in U-tube to reduce computational time.
- 7 preliminary assessments made in total.
- Highest outlet temperature (32 °C) and net energy flow rate (5.5 MWth) was for 5 km vertical depth in higher-strength rock environment.

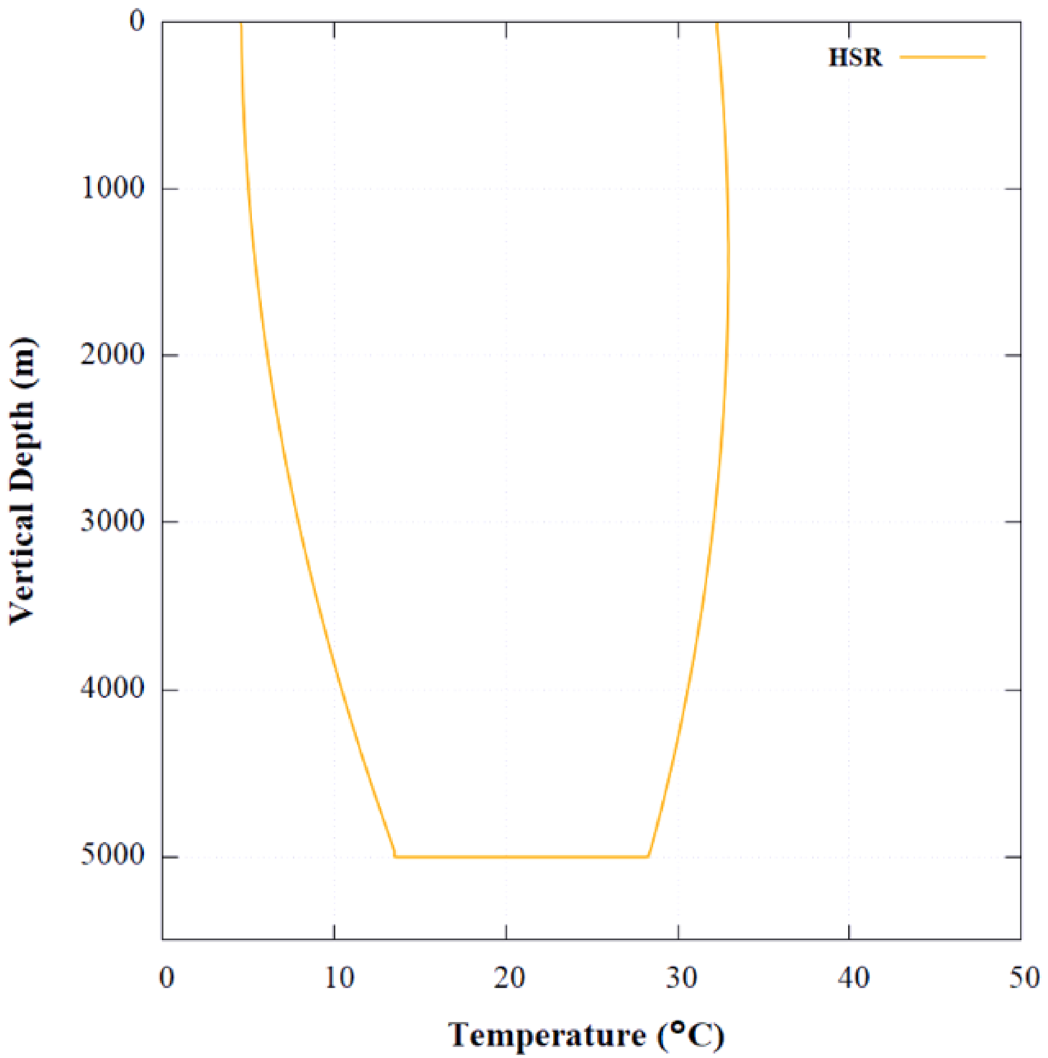

Figure 3. HSR 5 km temperature vs depth after 1 year

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Closed-loop geothermal system (CLGS) only

- Second study: sensitivity analysis of design in LSSR environment at 1 km vertical depth (Tahir et al 2023).
- Vary fixed mass flow rate, geometry radii, lateral length, thermal properties of host rock, long-term sustainability study of 10 years.
- ‘Best-case’ scenario: 2 kg/s, higher geometry in lateral, 2 km lateral length for higher outlet temperature.
- Future work: how temperature vs depth in conductive rock setting changes when CLGS design is combined with the heat source term study.
- More important factor: higher outlet T or higher energy flow rate for waste heat recovery?

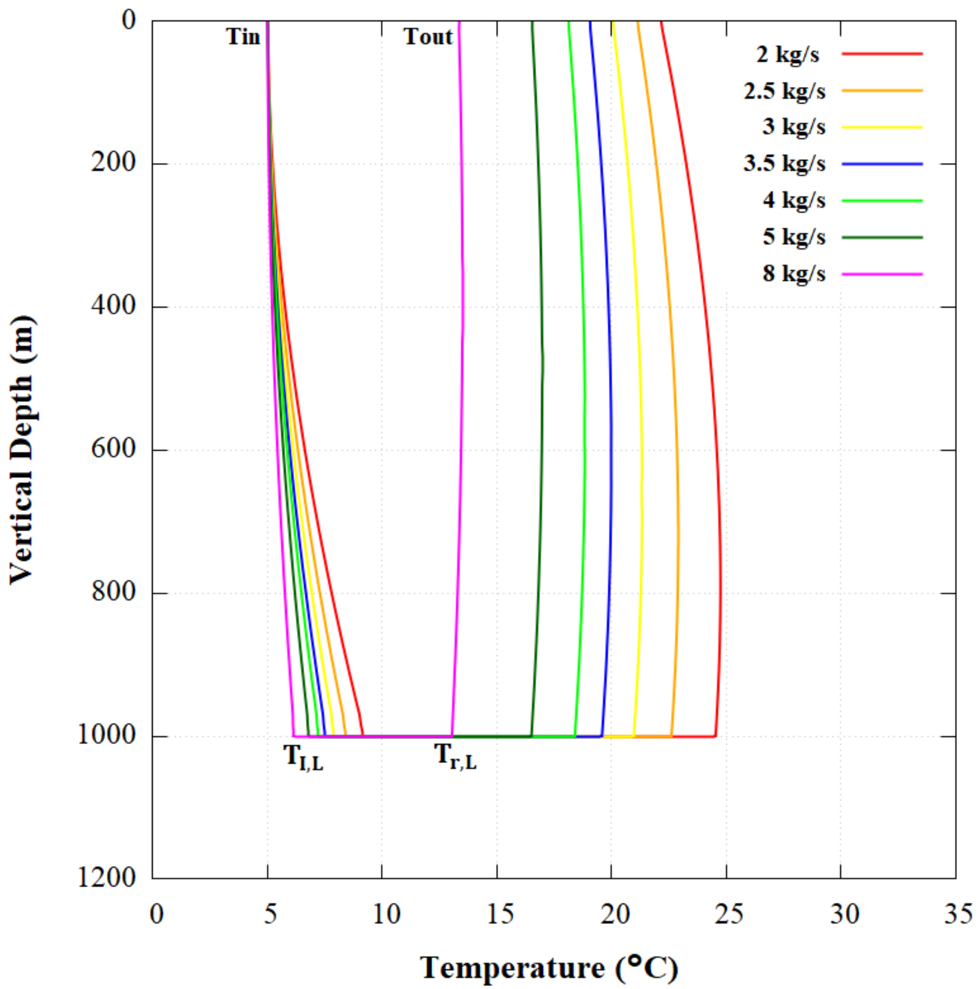

Figure 4: Mass flow rate study on CLGS in LSSR after 1 year

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