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Uncertainty Quantification of the Performance of a Deep Borehole Heat Exchanger at Newcastle Helix, UK

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ABSTRACT

Repurposing existing wells, including abandoned hydrocarbon wells, would significantly reduce the cost of deep geothermal developments. The Newcastle Science Central geothermal borehole, drilled in 2011 to a depth of 1820m, was intended to contribute to the energy mix of the Newcastle Helix redevelopment but the water yield proved insufficient. Our current project, Net Zero Geothermal Research for District Infrastructure Engineering (NetZero GeoRDIE), investigates the potential for repurposing the well as a closed loop coaxial deep borehole heat exchanger (DBHE) for heating and cooling. This study presents an uncertainty quantification of a conceptual DBHE at Newcastle Helix. The computational model is based on a recent fast semi-analytical solution, validated against a 3D finite element simulation undertaken in the open-source multi-physics software package OpenGeoSys. The model parameters are obtained from nearby geological data sources but a high degree of uncertainty surrounds several key physical and thermal parameters. We investigate the impact of geological uncertainties on the recoverable geothermal heat over the short and long-term (20 years) by using a probabilistic approach. We also conduct a global sensitivity analysis by computing the Sobol' indices from the coefficients of a polynomial chaos surrogate model. The results indicate that, in the operational scenario considered, potential DBHE production is around 140 kW over a 20-year design life (P50). Over time, the sensitivity of the fluid temperature to the input parameters evolves, revealing that the thermal properties of the rock become more important over the long-term: the recoverable geothermal heat is mainly controlled by the thermal properties of the deeper geological formations. The results offer valuable insights into the feasibility of repurposing existing deep wells as closed loop geothermal systems.

1. INTRODUCTION

Geothermal energy is increasingly seen as having an important role to play in the global drive towards net zero carbon emissions. The consistent availability of subsurface heat offers a stable energy source capable of meeting heating, cooling and baseload electricity demands. Rapid growth in geothermal energy is mainly limited by high initial capital costs, lengthy project development timelines and risks during initial exploration (DNV, 2023). Alongside the development of new geothermal technologies, such as enhanced geothermal systems or supercritical geothermal, repurposing existing wells, including abandoned hydrocarbon wells, could significantly reduce the cost of deep geothermal developments. Our current project, Net Zero Geothermal Research for District Infrastructure Engineering (NetZero GeoRDIE), investigates the potential for repurposing an existing deep well as a deep borehole heat exchanger (DBHE) for heating and cooling. The Newcastle Science Central geothermal exploration borehole was drilled in 2011 to a depth of 1820m and was intended to contribute to the energy mix of the Newcastle Helix redevelopment (the Science Central site was renamed in 2018) but the water yield proved insufficient (Younger *et al.*, 2016). However, its central urban location and proximity to the growing Helix site makes it an ideal candidate to explore repurposing options.

Extraction techniques for deep geothermal energy can be divided into open and closed loop systems. In an open loop, two boreholes are drilled, with one to inject cool water and one to extract hot water from the geothermal reservoir. In contrast, in a standard closed loop system, a single borehole is used to circulate cool water downwards from the surface, which then warms up along the length of the borehole before warm water flows back upwards. Due to developments in directional drilling technology, increasingly complex well configurations are now being explored to increase the efficiency of closed loop systems.

Given the lack of flow at the Newcastle Science Central borehole, repurposing strategies have focused on a simple closed loop or DBHE system in the existing borehole. DBHE performance is a function of borehole depth, geothermal gradient, the properties of the surrounding rock, and system design such as pipe configuration, flow rate and material choice (Piipponen *et al*, 2022). Although reservoir flow characteristics are not required, much of the uncertainty in predicting the likely heat output still lies in the thermal and physical characteristics of the geology; in this case, no core was recovered from the Newcastle Science Central borehole during drilling so laboratory core analysis to reduce these uncertainties has not been possible. Modelling of DBHE performance has advanced over the last decade, see Chen and Tomac (2023) for a review, but efforts at quantifying uncertainty in the system are often limited by the computational demands of complex numerical models.

In this study, we present an uncertainty quantification of a conceptual DBHE at Newcastle Helix, representing a potential repurposing scheme for the Newcastle Science Central borehole. The computational model is based on a recent semi-analytical solution, validated against a 3D finite element simulation undertaken in the open-source multi-physics software package OpenGeoSys. The model parameters are obtained from nearby geological data sources, but a high degree of uncertainty surrounds several key physical and thermal parameters.

We investigate the impact of geological uncertainties on the recoverable geothermal heat over the short and long-term by using a probabilistic approach. We also conduct a time-dependent global sensitivity analysis by computing the Sobol' indices from the coefficients of a polynomial chaos surrogate model.

2. NEWCASTLE SCIENCE CENTRAL BOREHOLE

Figure 1 shows the location, well construction, and lithostratigraphy of the Newcastle Science Central borehole. The Newcastle region, in North East England, is underlain by a Carboniferous sedimentary basin known as the Northumberland Trough. A full and detailed description of the drilling of the borehole, which began in 2011, can be found in Younger *et al.* (2016). The borehole reached a total depth of 1820m, passing through a succession of Carboniferous rocks including the Pennine Coal Measures, Millstone Grit Group, Yoredale Group (containing the Stainmore, Alston, and Tyne Limestone Formations) and the Border Group (present here as the Fell Sandstone overlying the Lyne Formation). The original target was the Fell Sandstone, which was identified between 1418m and 1795m depth. The quartz dolerite of the Whin Sill also makes an appearance in two intervals.

Due to budget limitations, there were several phases of drilling and casing activities, and some complications were encountered (see Younger *et al.*, 2016). In this study, we are considering a conceptual repurposing of the drilled borehole as a closed loop system, with the intention of investigating the impact of geological uncertainty on the recoverable heat; practical issues relating to the impact of existing casing, tubing and packers in the borehole are left to future work.

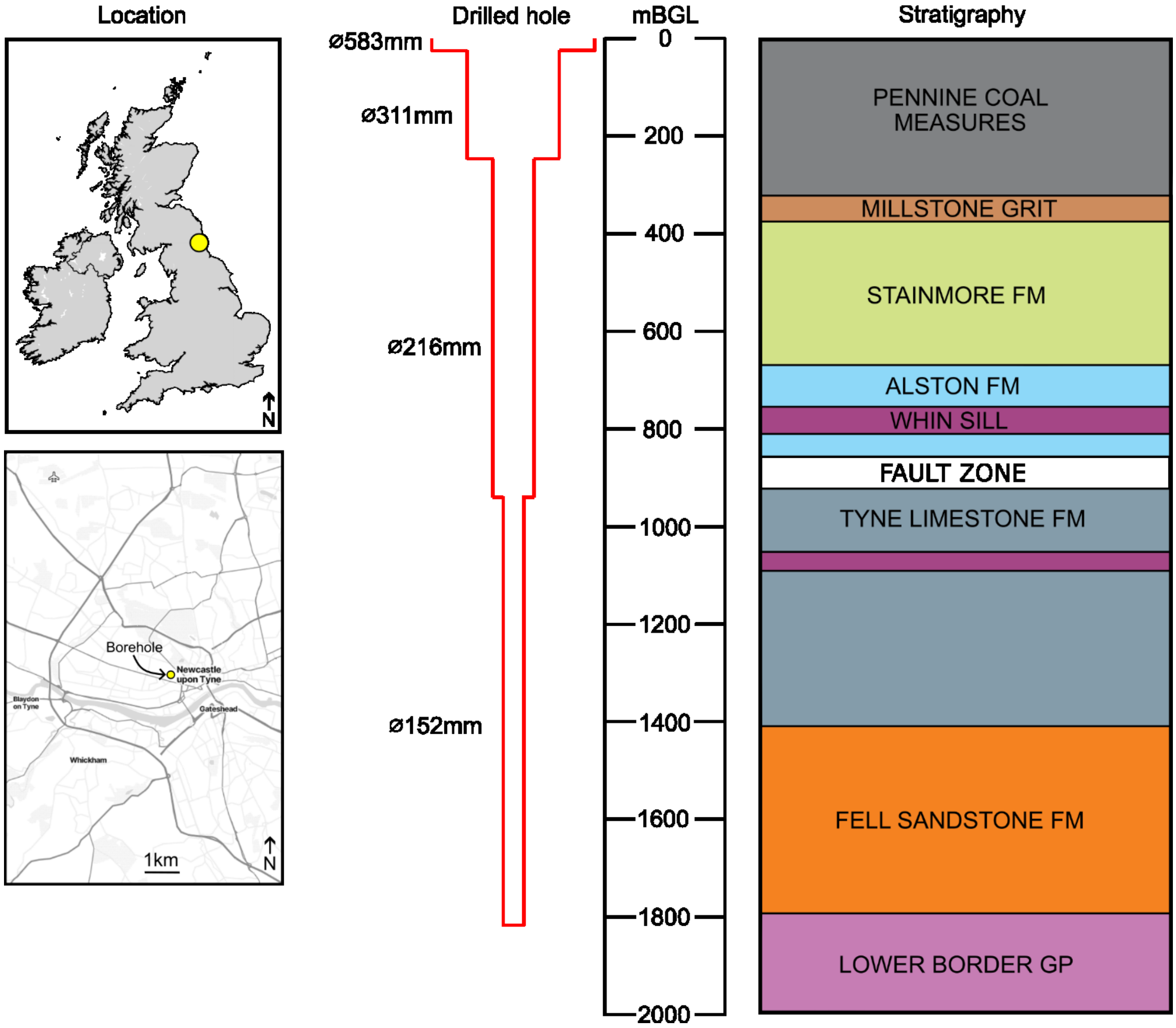

Figure 1: Location, drilled hole diameter, and simplified lithostratigraphy of the Newcastle Science Central geothermal borehole. GP = Group; FM = Formation.

3. METHODOLOGY

3.1 Framework for Uncertainty Quantification

Uncertainty quantification describes the process of defining uncertainties in the parameters of a model and quantifying their impact on the model outputs. The general framework is shown in Figure 2. We have applied this framework to quantify the impact of geological uncertainties on the performance of a DBHE at Newcastle Helix, and each step is described in subsequent sections. All computations are undertaken using the state-of-the-art UQLab software (Marelli and Sudret, 2014).

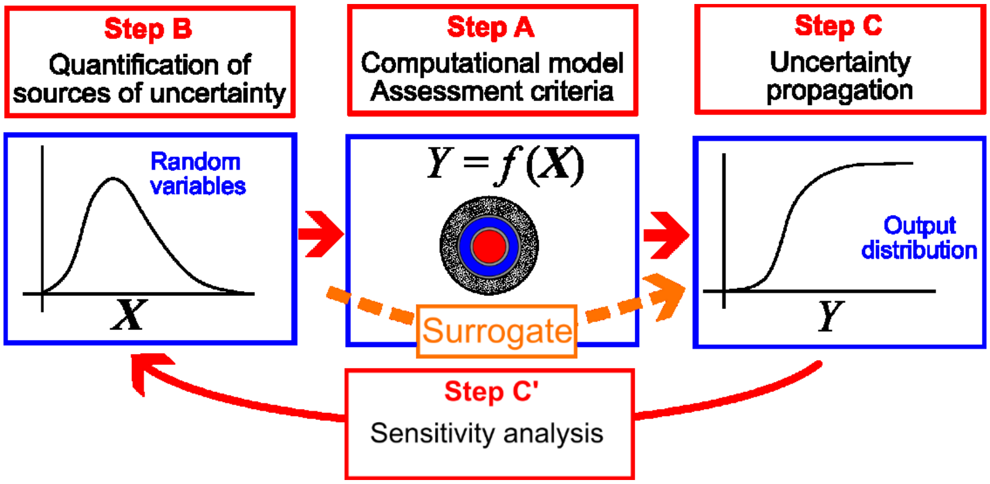

Figure 2: General framework of uncertainty quantification, after Sudret (2007).

3.2 Computational Model

The transient heat transfer model formulated by Beier *et al.* (2022) describes the performance of a coaxial DBHE in a multi-layer ground profile, considering the effect of a geothermal gradient. The model configuration is shown in Figure 2; for simplicity, we assume that the borehole has a constant diameter. We consider only the case of fluid entering the external (annular) pipe and flowing upwards through the internal pipe; this has been shown to be the more efficient flow direction for heat extraction (Holmberg *et al.*, 2016).

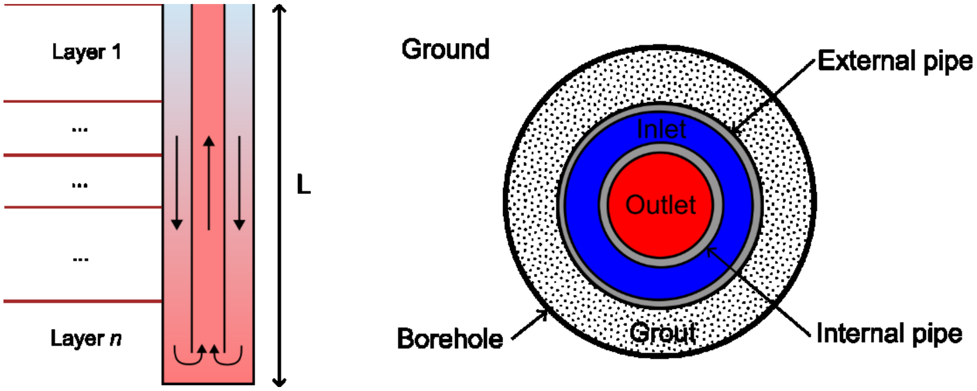

Figure 3: Schematic of a coaxial deep borehole heat exchanger (DBHE) of length L in a layered ground profile.

The semi-analytical model provides an estimate of the temperature profiles in the fluid in the internal and external pipes and in the grout and ground over time for a given heat extraction (or input) rate P.

We define the indicative geothermal power P_{DBHE}, as the maximum power that can be extracted from the borehole without dropping any part of the system below freezing (0°C) over the design life:

$$P_{DBHE} = \arg\min_{P} |\min(\Gamma(\boldsymbol{X}; P))| \tag{1}$$

where the model is a function of P and the vector of model parameters $\boldsymbol{X}$.

The system design is given in Table 1, specifying the borehole, pipe, grout, and fluid properties. The design was based on a steel external pipe and HDPE internal pipe with a water-saturated cement grout. A fluid circulation rate of 3 L/s was assumed as typical of a coaxial system of this depth (e.g. Piipponen *et al.*, 2022); further optimization of the design to limit pressure loss and increase heat recovery would be possible but is not the focus of this study.

Table 1: Borehole, pipe, grout, and fluid properties.

Property	Value
Borehole length (m)	1820
Borehole diameter (m)	0.152
Internal pipe outer (inner) diameter (m)	0.07480 (0.06104)
Internal pipe wall thermal conductivity (W/m/K)	0.45
External pipe outer (inner) diameter (m)	0.1300 (0.1138)
External pipe wall thermal conductivity (W/m/K)	52.7
Grout thermal conductivity (W/m/K)	1.05
Grout volumetric heat capacity (MJ/m^3/K)	1.824
Fluid flow rate (l/s)	3
Fluid density (kg/m^3)	998
Fluid viscosity (kg/m/s)	0.0008
Fluid specific heat capacity (J/kg/K)	4180
Fluid thermal conductivity (W/m/K)	0.59

3.3 Sources of Uncertainty

Here, we focus on assessing the impact of geological uncertainties, specifically the thermal conductivities of the various lithologies that the borehole is drilled through, alongside the subsurface temperature. All variables are assumed to be independent. Previous work has shown that, of the thermal and physical properties of the rocks, thermal conductivity has the most influence on DBHE performance. As mentioned, no conductivity measurements have been taken from the Science Central borehole but a set of thermal conductivity data is available from a borehole drilled 30km to the north (at Longhorsley, completed in 1986), also in the Northumberland Trough. The stratigraphy at the Longhorsley borehole is the same as at Science Central except that it begins at the Stainmore Formation (the Coal Measures and Millstone Grit are not present). 111 thermal conductivity readings were taken on chip samples and corrected for porosity as reported in Gebski *et al.* (1987); the data will soon be easily obtainable (Dickinson and Ireland, 2023). Figure 4(a) shows the thermal conductivity measurements with depth.

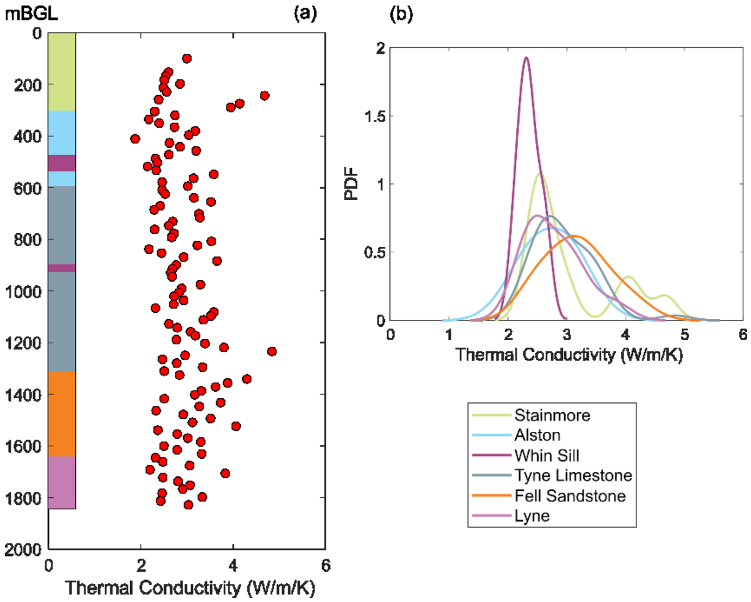

Figure 4: (a) Thermal conductivity with depth from the Longhorsley borehole, and (b) PDFs of each formation.

Kernel density estimation (KDE) is used to approximate the probability density function (PDF) of thermal conductivity from each formation, as shown in Figure 4(b). The statistics (mean and coefficient of variation, COV) are presented in Table 2. For the Coal Measures, Millstone Grit and fault zone, the mean was taken from Kolo *et al.* (2022), who calculated a value based on typical conductivities from the constituent lithologies, and the COV was set at 0.2 which appears typical of the Carboniferous formations in the Northumberland Trough. Beta distributions were selected as qualitative descriptions of the parameter variability. The density and specific heat capacity of the various formations are taken from Kolo *et al.* (2022).

Several temperature measurements were taken while drilling the Science Central borehole: for example, 73.3°C was recorded at 1772m depth in August 2012. The temperature log in Younger *et al.* (2016) suggests that assuming a constant geothermal gradient will give a reasonable approximation of the true profile. Given the regional average surface temperature of 9°C (Met Office, 2023), the temperature gradient for this instance was 36.3°C/km. We assumed a low uncertainty in the geothermal gradient (COV = 0.02) to model potential variations in the downhole temperature.

Table 2: Characterization of random variables: thermal conductivity and temperature.

Thermal Conductivity			
Formation	PDF	Mean (W/m/K)	COV
Coal Measures	Beta	2.35	0.2
Millstone Grit	Beta	2.9	0.2
Stainmore	KDE	3.06	0.26
Alston	KDE	2.73	0.17
Whin Sill	KDE	2.36	0.08
Fault Zone	Beta	2.75	0.2
Tyne Limestone	KDE	2.95	0.17
Fell Sandstone	KDE	3.17	0.17
Lyne (Lower Border Group)	KDE	2.78	0.17
Temperature			
Property	PDF	Mean (°C/km)	COV
Geothermal Gradient	Beta	36.3	0.02

3.4 Uncertainty Propagation

The semi-analytical model is fast, with run-times <1min depending on the chosen number of timesteps and pipe elements. However, a global sensitivity analysis can require $10^4 \times d$ model evaluations, where d is the random dimension (Iooss and Lemaître, 2015). For this reason, we speed the analysis up by exploiting a surrogate model, specifically a polynomial chaos expansion (PCE). As illustrated in Figure 2, the surrogate model replaces the computational model in mapping the input random variables to the output space. The model output can be approximated by expanding the response quantity, Y, onto a basis of orthonormal multivariate polynomials. If the model is a function of M independent input random variables $\boldsymbol{X} = \{X_1, \dots, X_M\}^T$, this can be written as follows:

$$Y = \Gamma(\boldsymbol{X}; P) = \sum_{\boldsymbol{\alpha} \in \mathbb{N}^M} c_{\alpha} \Psi_{\alpha}(\boldsymbol{X}) \tag{2}$$

where $\Psi_{\alpha}(\cdot)$ is a multivariate polynomial basis and c_{α} are deterministic coefficients which must be computed, for example by least squares regression from a set of model evaluations. The multi-index $\boldsymbol{\alpha} = \{\alpha_1, \dots, \alpha_M\}$ represents the polynomial order associated with each random variable. The series is known as a polynomial chaos expansion; full detail can be found in, for example, Marelli *et al.* (2022). Here, we construct sparse PCEs using the least angle regression approach. Jacobi polynomials are associated with the beta distribution and the Stieltjes procedure is used to create an orthonormal polynomial basis for the KDE-based distributions. The coefficients are computed from a set of 200 model runs with Latin Hypercube sampling of the input variables. For the transient simulations, the model outputs temperatures at each time step. We adopt the 'time-frozen' PCE approach of computing a separate PCE at each timestep; given the constant heat extraction rate, this is found to perform well.

3.5 Global Sensitivity Analysis

A further advantage of using PCEs for uncertainty propagation is that the coefficients of the expansion can be used for global sensitivity analysis. Here, we directly compute the Sobol' indices in a post-processing step. The Sobol' indices are a variance-based sensitivity method based on a decomposition of the total output variance into a sum of components that are functions of the input random variables; the PCE can be organized in this way, hence leading to a direct sensitivity computation (Marelli et al, 2022). The first order (or *main effect*) Sobol' sensitivity indices are:

$$S_i = \frac{\mathrm{Var}\left[\mathbb{E}[Y|X_i]\right]}{\mathrm{Var}[Y]} \tag{3}$$

where $\mathbb{E}[Y|X_i]$ is the expectation of the model output Y conditional on the input variable X_i and $\mathrm{Var}[\cdot]$ is the variance. The equation can be interpreted as the proportion of the total variance attributable to variable X_i alone. Multiple-term indices, such as S_{ij}, are higher-order Sobol indices that account for the interactions between variables. Total Sobol' indices can also be defined as the sum of all Sobol' indices involving a particular variable.

4 RESULTS AND DISCUSSION

4.1 Model Validation

First, we conduct a validation of the semi-analytical model of Beier *et al.* (2022) using a separate numerical solution. The finite element (FE) software OpenGeoSys (Bilke *et al.*, 2022) is used to simulate the DBHE, with 50kW extracted continuously over a period of 6 months (180 days). OpenGeoSys implements the 1D DBHE element formulated by Diersch *et al.* (2011) and models the heat transfer with the surrounding porous rocks. The borehole is setup according to Table 1 and the stratigraphy is that shown in Figure 1. Mean values of the parameters are adopted. The 50kW heat extraction begins after 4 hours; prior to this, the fluid is circulated through the borehole by a pump at 200W. Figure 5 shows the inlet and outlet temperatures over time from both models on a logarithmic time axis. We note that the FE model requires a run time of more than 4.5 hours. There are some minor differences in the initial temperature increase predicted by the two models in the circulation period but in general, a good match is observed between the two solutions. The long-term decline in inlet/outlet temperature due to heat extraction is well captured by the semi-analytical model.

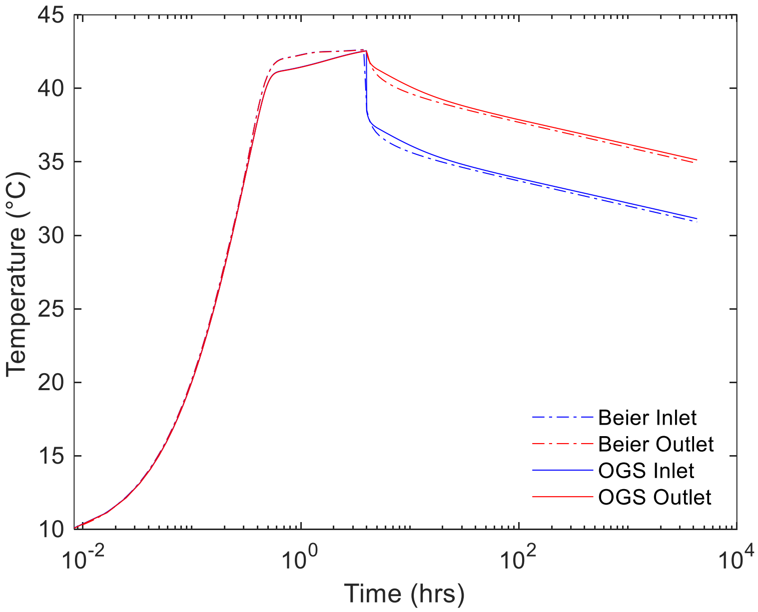

Figure 5: Comparison of semi-analytical (Beier) and finite element (OGS) models.

4.2 Transient Response

To assess the effect of geological uncertainty on the performance of the DBHE, we propagate the input uncertainties (Figure 4) through the semi-analytical model according to the methodology set out in Section 3. As previously, a constant 50kW of heat is extracted after a 4 hour circulation period, but the simulation time is now extended to 20 years, which might represent the design life of a heat network for example. Figure 6 shows the 'deterministic' inlet temperature (with mean properties adopted) alongside 1000 realizations of the PCE surrogate model (note that the leave-one-out error is less than 10^{-4} at each step, meaning that the prediction error is minimal). The PCE mean is also shown, representing the mean response, and this can be seen to fit closely to the deterministic analysis. The geological uncertainty results in a range of inlet temperatures, with the variance tending to increase with time due to the long-term temperature decline following different trajectories.

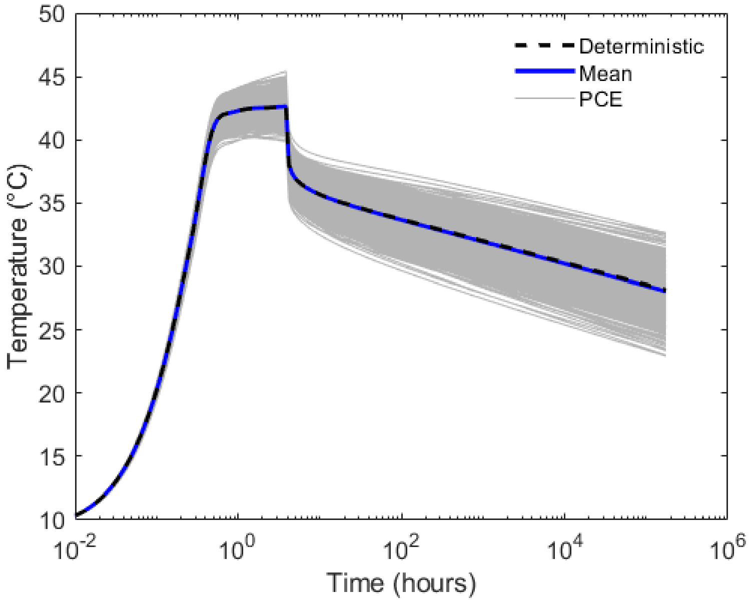

Figure 6: PCE realizations of the inlet temperature over time. Deterministic and mean response also shown.

Figure 7 shows the evolution of the total Sobol' sensitivity indices over time for the inlet temperature. In the circulation period, the geothermal gradient controls the response and the shallow Coal Measures is the most influential geological strata. The influence of the geothermal gradient declines rapidly: after 10 hours, the geology controls over half of the variance, and after 100 hours, the Fell Sandstone, which has the highest mean thermal conductivity, becomes the dominant variable. The deeper formations are the most influential in the long term with the Tyne Limestone (which becomes the secondary variable after 20 years) and Fell Sandstone both deeper than 900m; the effect of the shallow strata (Coal Measures and Stainmore) shows a steady decline after heat extraction begins. We note that interaction between variables is limited and the total Sobol' indices sum to approximately 1 throughout the simulation time.

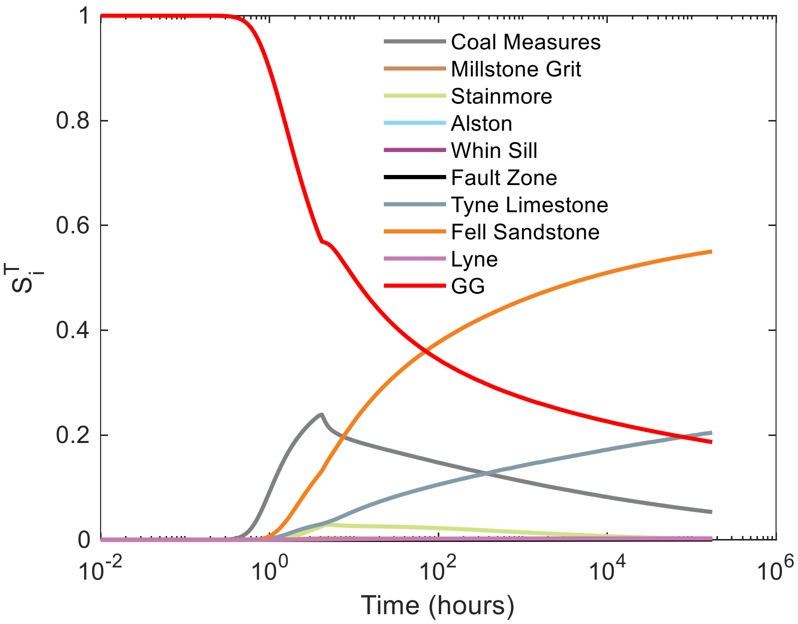

Figure 7: Total Sobol' indices over time for inlet temperature. GG = geothermal gradient.

4.3 Long Term Heat Output

The heat output is defined by Equation (1). We again consider a time period of 20 years with a constant heat extraction beginning after 4 hours. Figure 8(a) shows the PCE-generated PDF of recoverable geothermal heat (measured in kWth). The modal output (P50) is 142.7 kW with P90 and P10 values of 132.0 and 153.5 kW respectively. The COV is 0.059, which is relatively low compared to the input variability and suggests that the recoverable power (in the considered operational scenario) can be estimated quite accurately, even with the current data limitations. The Sobol' indices shown in Figure 8(b) demonstrate that the variance of the heat output is primarily controlled by the thermal conductivity of the deeper ground layers.

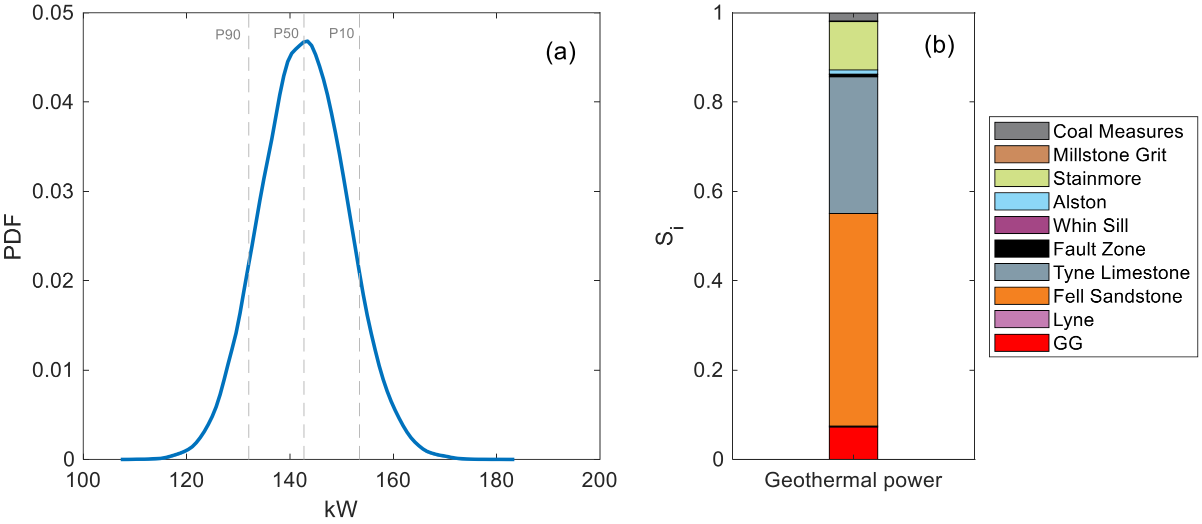

Figure 8: (a) PDF of geothermal heat output, and (b) first order Sobol' sensitivity indices.

5. CONCLUSION

In this paper, we have investigated the effect of geological uncertainty on the performance of a conceptual 1820m-depth DBHE at the Newcastle Helix site in Newcastle upon Tyne, UK. The DBHE design is based on repurposing the existing Science Central deep geothermal exploration borehole as a coaxial closed loop system. Due to the limited amount of data collected during the drilling of the borehole in 2011, there is considerable uncertainty surrounding the physical and thermal properties of the rocks surrounding the borehole. We used data from a nearby borehole (also in the Northumberland Trough) to estimate the moments and PDFs of thermal conductivity in the various formations. The temperature was relatively well-constrained during construction of the Science Central borehole, and so a low uncertainty was assumed for the geothermal gradient. We used a fast semi-analytical model to predict the performance of the DBHE; the model was validated against an FE solution which simulates the heat transfer between a 1D DBHE element and a surrounding porous medium. Using PCEs to propagate the input uncertainty through the model, the results demonstrate how the geological uncertainty causes a range of predicted inlet and outlet temperatures, with the variance tending to increase with time and the controlling variable changing from the geothermal gradient in the short term (< 100 hours) to the deep Fell Sandstone, which has a relatively high thermal conductivity. Assuming constant heat extraction over 20 years, the recoverable heat is between 132 (P90) and 153 kW (P10). This might be further optimized by revisiting the DBHE design and by reducing uncertainty in the thermal properties of the rocks surrounding the borehole.

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