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Performance Assessment Using Numerical Models for Thermal Energy Storage and Transport via Underground Mine Workings

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ABSTRACT

The Galleries2Calories (G2C) project is part of the Geothermica Consortium, including partners from Scotland, Ireland and the USA. It investigates the use of legacy mine workings for thermal energy storage and transport networks in Edinburgh, Scotland. The concept, called the Geobattery, is to inject heated water from a data center to abandoned flooded coal mine workings that will convey the water kilometers downstream, where it can be used for district heating. The project could provide a sustainable clean solution for home heating potentially applicable to many other locations with waste heat and abandoned mine workings in the UK and globally. However, the storage and transport of waste industrial heat in mine workings is challenging due to the complexity and uncertainty of the interconnected and often collapsed nature of the mine workings. The US teams (Lawrence Berkeley National Laboratory and Idaho National Laboratory) are using numerical models to assess both short-term and long-term thermal performance of the Geobattery and to study potential design variations and risks. Here, we present these model studies and potential implications to the project.

1. INTRODUCTION

The Geobattery concept, as its name implies, is to use the earth as a battery for long-term energy storage, either as cold or hot energy. Figure 1a shows the schematic of how such a system works through mine workings, i.e., injecting waste energy stored in liquid water into subsurface mine workings (or high-permeability layers), and recovering the energy at a different location, through a heat pump or another technology. In theory, the system could provide sustainable and low-carbon energy by recycling waste heat, while thermal efficiency/performance depends on the individual project implementation/operation.

The Galleries2Calories (G2C) project, which is part of the Geothermica Consortium, including partners from Scotland, Ireland and USA, investigates applying the Geobattery concept at the underground legacy mine workings near Edinburgh, Scotland (Figure 1b). The plan is to use mine waters to cool a large high-performance Advanced Computing Facility (ACF) at the University of Edinburgh as shown in Figure 1b. The liquid coming out of the ACF with an elevated temperature, in this case, at 40°C, will be injected back into the legacy mine workings. The waste heat (heated water) will flow down gradient, and can then be withdrawn for seasonal heating purposes.

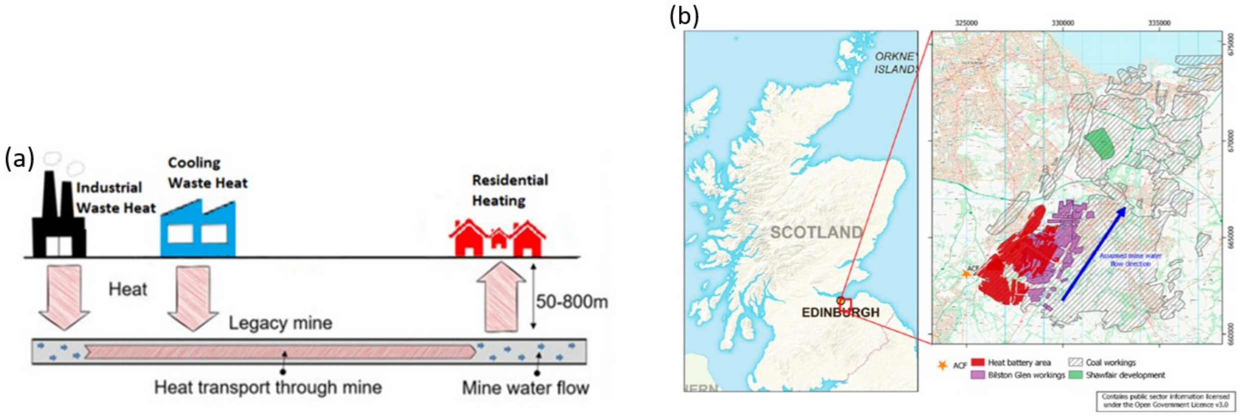

Figure 1: (a). Schematic of Geobattery concept using mine workings; and (b) the location of the G2C project.

While the team from the Idaho National Laboratory (INL) investigates the potential thermal-hydrological response to Geobattery operation using a detailed topology-based 3D model, scientists from Lawrence Berkeley National Laboratory (LBNL) built a few sets of simplified models and performed first-order analysis to understand thermal arrival time and temperature change at the production well located in the vicinity of the heat users, about 5 km from the injection well located near the ACF.

2. SITE DESCRIPTION

As illustrated in Figure 2, three collieries exist within the Geobattery footprint: Roslin, Burghlee, and Ramsay, with groundwater flow from Roslin to Ramsay. At the Roslin shaft, the coal seam separation ranges from 17 m to 55 m, with most seams separated by about 35 m, and the pit bottom is at a depth of 280 m. Most of the coal seams appear in all three collieries, and some show hydraulic connectivity between them, indicated by red dashed lines in Figure 2(a). These are the primary pathways for water flow in the Geobattery.

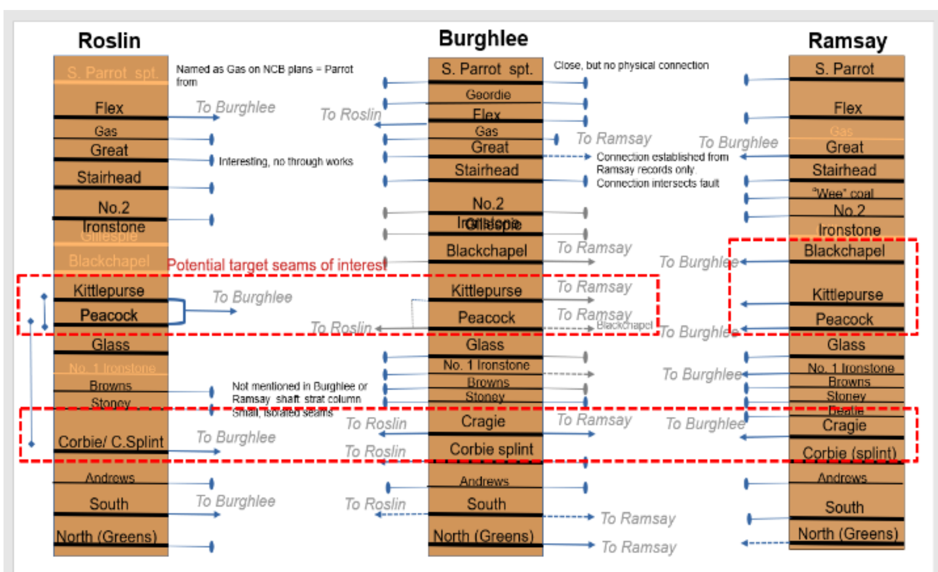

Figure 2: Named coal seams in each of the three collieries. The red dashed lines indicate seams that have known hydraulic connection between collieries. Courtesy of Dr. Samuel Graham, University of Edinburgh.

3. THERMAL-HYDROLOGICAL MODELS

Doughty et al. (2024) provided a summary of previous modeling studies related to using underground mine workings for geobatteries, including Todd (2023), Receveur et al. (2022), Mouli-Castillo et al. (2023) and Perez Silva et al. (2022). Here, we are not repeating the summary of these studies. Our modeling study presented below will focus on the integrated system (i.e., injection of heated water at ACF and withdrawal 5 km downstream) thermal performance.

3.1 Simplified Conceptual Representation of the System

The INL team has built a large-scale 3D detailed model, incorporating all known features, geometry and details of the structure of the three collieries to investigate system performance (Doughty et al., 2024; Atkinson et al., 2024). Not repeating the same effort, the LBNL team focused on the main features of the system, and made abstractions of the system, as shown in Figure 3, to understand the potential system uncertainty. As shown in Figure 2, the Corbie seam is hydraulically connected between all three collieries. However, it is not clear whether and how well the Peacock coal seam is connected between Burghlee and Ramsay. As it is identified as one of the potential target seams of interested, the hydraulic connectivity is assumed in the initial analysis. Based on this assumption, the LBNL team included two connected workings (indicated by the horizontal thick grey lines) in the conceptual representation, as shown in the vertical profile of the LBNL simplified model in Figure 3. These coal workings mainly consist of pillars and rooms – a system in the old mines to allow the coal to be stripped out while pillars are holding up the formation. The layout of the pillar and room system (Young and Adams, 1999; Todd, 2023) is shown in Figure 3. The dimensions may vary in different workings.

In addition, an important assumption is made in the models described below: fluid flow and heat transport through mine workings (Pillar and Room (PR) system) can be modeled as flow in a fractured porous medium. This assumption is justified by the fact that the PR system only involves single phase liquid flow, and simulations are performed by specifying injection/withdrawal rates, rather than pressure. The main interest of this investigation is the thermal performance of the system. The effects of pressure are not investigated in this study.

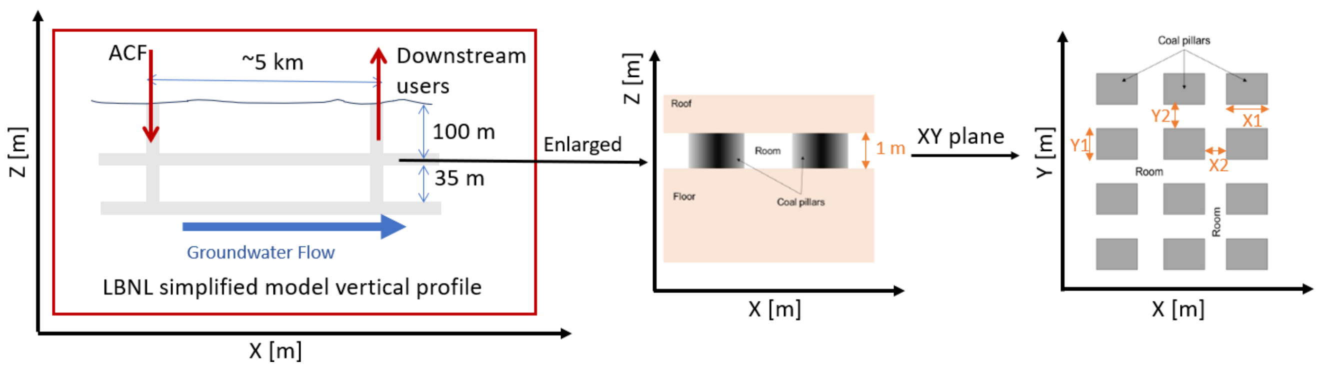

Figure 3: Schematics of LBNL's simplified model of the actual system (left), and cross section view (middle) & plan view of a simplified layout of a pillar and room working adapted from Younger and Adams (1999), and after Todd (2023). Horizontal grey area (left) indicates connected mine workings, with pillar/room setups shown in the other two figures. For the base case scenario, it is assumed X1=12m, and X2=Y1=Y2=6m. The actual dimensions/sizes may vary.

3.2 Description of the Three Models

Three models are built to simulate the above system. All models have the same vertical extent (from ground surface to 237m depth) and discretization. For the base case scenario, it is assumed that the pillar and room (PR) systems extend 10120m – 15200m in the X-direction, which is aligned with groundwater flow direction, from Roslin upstream to Ramsay downstream. In the Y-direction, the PR system is assumed to extend for 1200m. However, all models included at least extra 5 km of host rock both upstream and downstream in the X-direction to maintain the natural groundwater flow gradient, and in the Y-direction to account for heat loss to the sides.

To reduce the computational cost, 1) we assume the system is symmetric in the Y-direction, therefore, only half of the model domain is included in the Y-direction (0~600 m) as shown in Figure 4, indicated by the dash-dot red line, and 2) we ignore the asymmetric flow in the Z-direction, and as a result, we can include only the upper working, so that the vertical model extends from 0 to 118.5 m depth.

The three models considered in the analysis are:

- Model 1 – Explicit room and pillar (ERP): In this model, discretization is based on the dimensions/assumed setup of the pillar and room, as indicated in the caption of Figure 4. Properties of host rock, rooms and pillars as listed in Todd (2023) are used.
- Model 2 – Dual porosity model (DPM): In this model, the pillar and room are modeled using the classical double – porosity concept (Warren and Root, 1963) that was developed to model a fracture network with embedded low permeability rock matrix. Fracture and matrix properties are taken from rooms and pillars, respectively.
- Model 3 – Equivalent continuum model (ECM): Effective properties are calculated based on the sizes and properties of the PR system, and these properties are used for the PR system uniformly in the 1 m thickness layer.

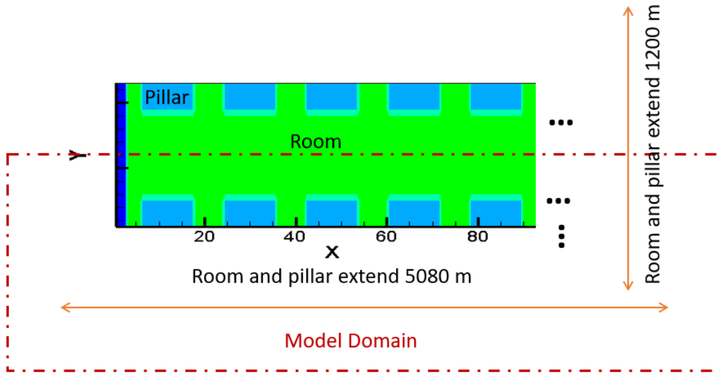

Figure 4: Schematic of a model that explicitly models the PR system. The actual model domain extends farther than what is shown here to provide the pillar and room system boundary conditions.

The properties used in each model are listed in Table 1. Most parameters are Todd's (2023) mean values, but a few are mean minus 0.5 standard deviations (why). The only parameter for which the distinction is likely to be significant is thermal conductivity, where the use of 0.78 W m^{-1} K^{-1} rather than the mean value of 1.35 W m^{-1} K^{-1} will inhibit heat transfer between rooms and pillars somewhat. This in turn will make it more difficult for Models 2 and 3 to adequately represent Model 1. Thus, use of this parameter provides a conservative test of the adequacy of Models 2 and 3.

Table 1: Formation properties used in the three models. Pillar (matrix), room (fracture) and host rock properties are taken from Todd (2023). Most values are Todd's mean values; those marked with a * are mean minus 0.5 standard deviations. Effective properties of model 3 are calculated based on size of pillar and room for the base case scenario (X1=12m, X2=Y1=Y2=6m).

		Permeability in X direction	Permeability in Y direction	Porosity	Density	Specific heat capacity	Thermal expansivity	Thermal conductivity
		m^2	m^2	-	Kg m^{-3}	J kg^{-1} K^{-1}	K^{-1}	W m^{-1} K^{-1}
Host rock (all models)		5.0e-13	5.0e-13	0.215	2500	1050	5.4e-5	3.25
Model 1	Pillar	2.0e-13*	2.e-13*	0.02*	1700*	1200	4.7e-5	0.78*
	Room	1.e-8	1.e-8	1.0	1000	4184	2.1e-4	0.6
Model 2	matrix	2.0e-13	2.e-13	0.02	1700	1200	4.7e-5	0.78
	fracture	1.e-8	1.e-8	1.0	1000	4284	2.1e-4	0.6
Model 3	Equivalent continuum	5.e-9	3.3e-9	0.67	1700	1200	4.7e-5	0.64

3.3 Simulation Tools

Simulations for Model 1 were performed using TOUGH4 code (https://lbl-1.gitbook.io/tough4-user-manual), while the ones for Model 2 and Model 3 were performed using iTOUGH2 code (Finsterle, 2004). The TOUGH family of codes (http://tough.lbl.gov) developed at LBNL is a suite of software for modeling multi-dimensional, multi-component, multiphase and heat in porous and fractured media. TOUGH4 is a re-engineered version from TOUGH2/3, taking advantage of using the hybrid parallel computing hardware and using well-known third-party software libraries. Due to the explicit modeling of pillar and room and large dimensions of the model domain, using TOUGH4 can significantly speed up the simulations. iTOUGH2 (**i**nverse **TOUGH2**) is a computer program that provides inverse modeling capabilities and forward model enhancements (Finsterle, 2023) for the TOUGH2 code; some of these capabilities (for example, specifying permeability zone as shown in later analysis) are used here.

The investigations below are focused on:

- Model choices: do the models produce significantly different results? Can these models validate each other, and can we use the fastest model for subsequent analysis?
- Impact on system thermal performance due to uncertainty in

- Initial groundwater flow velocity
- Geometry of the system and its connectivity
- Pillar/room size,
- Host rock thermal conductivity

4. MODEL ANAYLSIS AND RESULTS

To set up the initial conditions of the models, hydrostatic pressure, considered as reference pressure, is imposed on the downstream boundary elements. Pressures calculated based on groundwater gradient and reference pressure are imposed on the upstream boundary elements. System initial temperatures are calculated based on the assumed surface temperature (15°C) and the assumed geothermal gradient (25°C/km). Initial pressures are obtained by running the model to steady-state conditions.

4.1 Model Choices

To compare the three models, we use the scenario in which the groundwater gradient is assumed to be 0.02.

Figure 5 shows the temperature profiles at the production well for 50 years for three models, as well as the contoured temperatures at 50 years in the PR system. Different temperature fronts in the pillars and rooms can be observed from the EPR model. The models do not produce identical results, but they are close enough to provide confidence in using the ECM model for further analysis. This is due to the size of a pillar being much smaller compared to the thermal penetration depth in the coal seams (for example, 19 meters at 5 years, Doughty et al., 2024). As a result, the ECM will be used for further analysis as it has fewer grid blocks and runs much faster compared to the other two models.

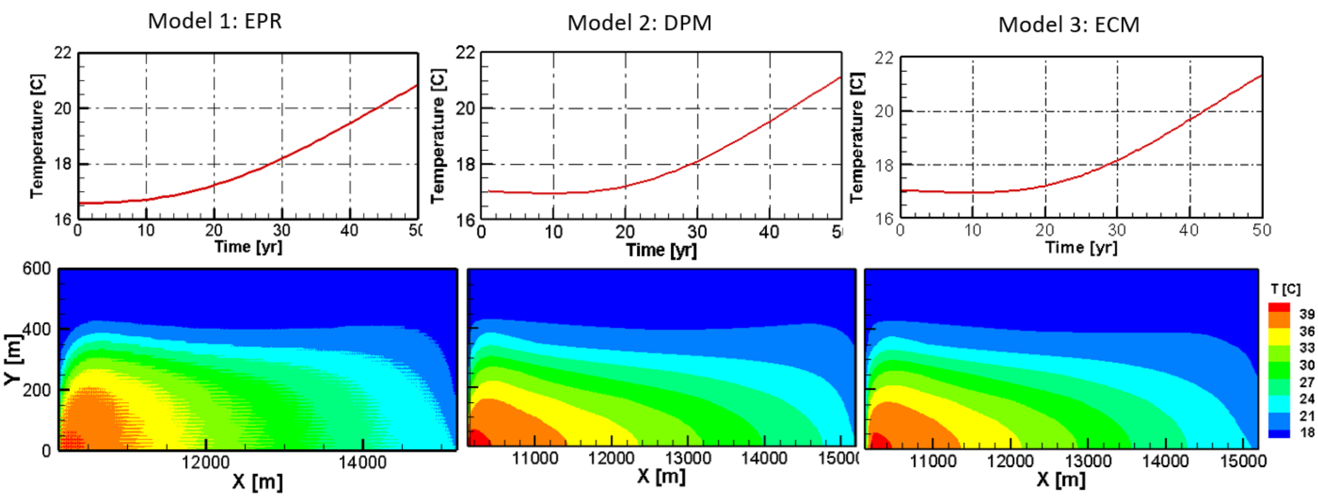

Figure 5: The upper panel shows the produced-water temperature (T_{pw}) over 50 years from all three models. The lower panel shows the temperature contour in the PR system from all three models. Notice only the region of the PR system is shown, as the host rock included for boundary condition is not shown here. The temperature shown from the DPM is the fracture temperature.

4.2 Impact of Groundwater Flow Velocity

The groundwater flow velocity is unknown for the target workings. In addition, it varies with locations and times, with potential discharge from other locations. Based on personal communications with Alejandro Perez Silva from the University of Edinburgh, the hydraulic gradient in the region could be around 0.01~0.02. As a result, three hydraulic gradients are considered in the simulations: 0.02, 0.01 and 0 (i.e., no groundwater flow). Again, produced temperature and temperature contours at 50 years for the PR system for the three cases are shown in Figure 6. Due to the large distance between the injection/production wells, in the case without groundwater flow, the flow near the wells is almost radial flow. Even with a hydraulic gradient of 0.02, the produced temperature at 50 years is only around 21°C for this scenario. This points out the impact of groundwater flow and the importance of having a good understanding of the flow velocity.

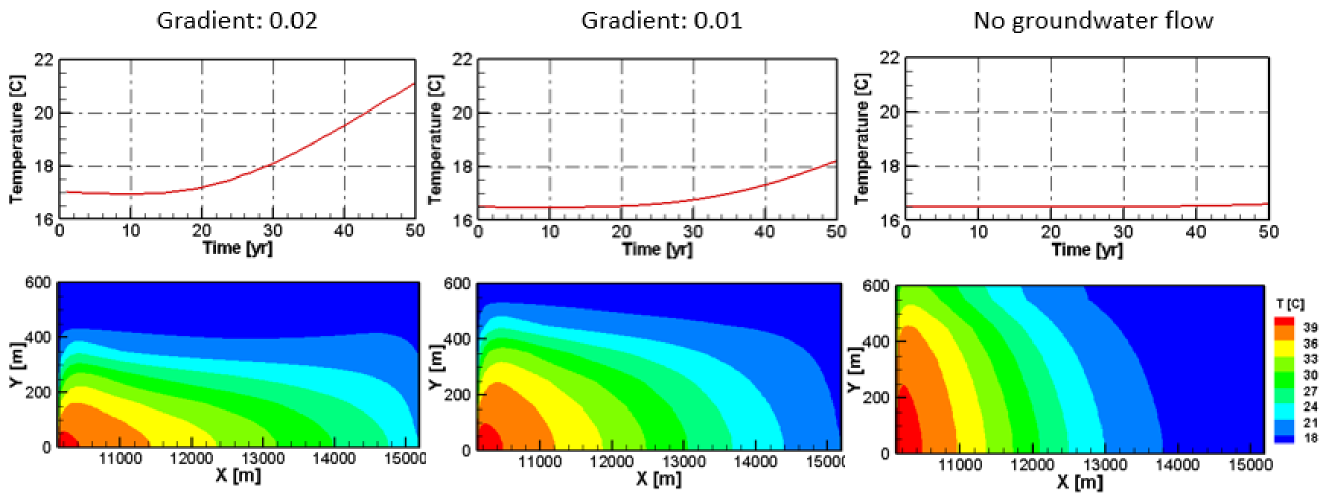

Figure 6: T_{pw} over time from all three gradients (upper panel) and temperature contour in the PR system at 50 years (lower panel) for various hydraulic gradients. Results are from Model 3 (ECM).

4.3 Impact of PR system geometry and connectivity

Although a uniform width (600m for half model) is assigned to the PR system, in reality it varies (see Figure 1b). To understand how this may affect the system, two additional scenarios were performed. The setup of host rock vs. PR system for these two scenarios are shown in the upper panel of Figure 7.

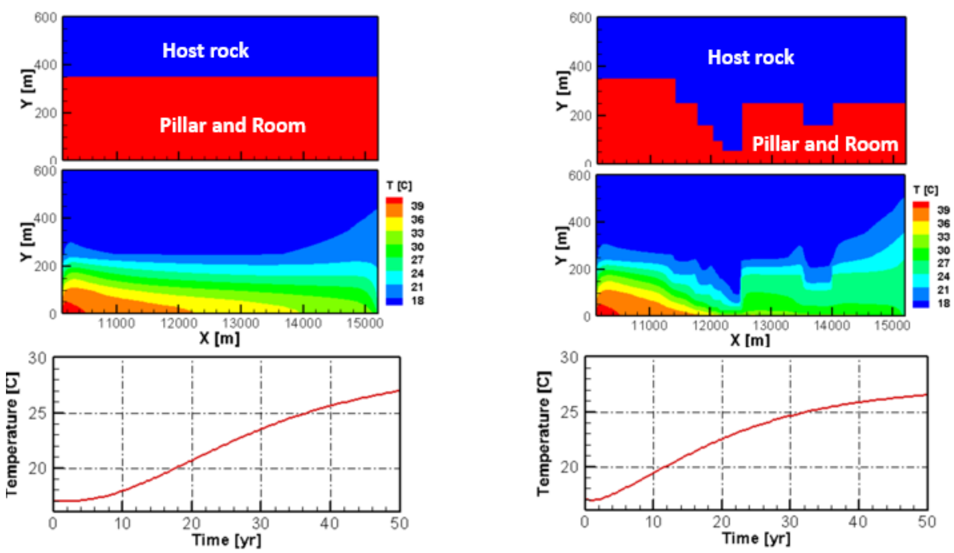

Figure 7: Additional models and simulations to investigate PR system geometry (upper panel), temperature contour at 50 years (middle panel), and T_{pw} profile over time (lower panel). Results are from Model 3 (ECM).

Narrowing the PR system, which has higher permeability than host rock, results in less spread in the Y direction and higher velocity in the X direction, and therefore, less heat loss to the host rock. This can lead to an earlier thermal arrival time and higher produced-water temperatures. Without considering its implication to pressure and geomechanical effects, this could be beneficial. The contour figures also show a slight increase of temperature at the host rock/PR system interface near the production well. This is due to the flow distortion of the flow field, where the bending of the flowlines from the prevailing ambient-flow direction is caused by the presence of a high permeability region, as pointed out by Harte et al. (2024).

As mentioned earlier, it is not clear how well the Peacock seam is connected between Burghlee and Ramsay. A simulation is performed assuming that there is only one connected pathway between the injection/production well, and that the pathway width is 600m. Figure 8 shows the produced temperature for this case, which is around 21°C at 10 years and more than 30°C at 50 years. This further demonstrates the potential of enhanced thermal performance if the waste heat can be contained within one narrow connected flow path.

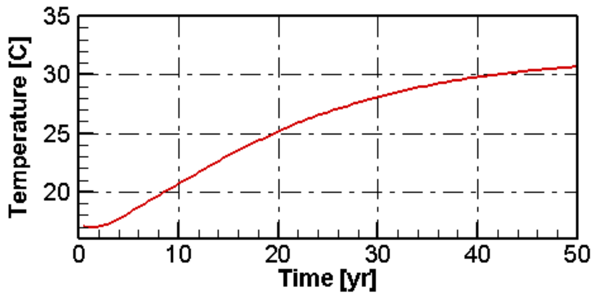

Figure 8: T_{pw} over time for a case with only one connected flow path.

4.4 Impact of Pillar/Room Size

Given the time and length scale of the studied system, no significant temperature difference is expected at the production well for different pillar/room sizes. The main implication for having a different size of the pillar and room other than the base case, is that the effective properties for the ECM model calculated in Table 1 will be different. Table 2 lists the corresponding properties for the sizes investigated.

Figure 9 validates the prediction that no significant difference exists among these scenarios in terms of produced-water temperatures. This is because the T_{pw} is mainly determined by the heat loss to the host rock, affected by the thermal properties of the host rock. For the studied scenarios, the maximum difference in the T_{pw} at 50 years is 1°C. However, the T_{pw} is also determined by the flow velocity in the X direction, therefore, the effective permeability of the PR system. The best thermal performance comes from Scenario 3, with a high effective permeability in the X direction (kx), and a high anisotropy ratio (kx/ky). The worst thermal performance is from Scenario 4, with the lowest anisotropy ratio (kx/ky).

Table 2: Investigated pillar and room sizes and corresponding effective properties (calculated).

Scenario number		1	2	3	4	5	6
Size (m)	X1 (pillar in X direction)	12	6	12	2	6	1.5
	X2 (room in X direction)	6	6	6	6	1.5	6
	Y1 (pillar in Y direction)	6	6	6	12	6	1.5
	Y2 (room in Y direction)	6	6	12	6	1.5	6
Effective properties	Porosity	0.67	0.75	0.78	0.83	0.36	0.96
	Permeability_x (m2)	5.00E-09	5.00E-09	6.67E-09	3.33E-09	2.0E-09	8.0E-09
	Permeability_y (m2)	3.33E-09	5.00E-09	3.33E-09	7.50E-09	2.0E-09	8.0E-09
	Thermal conductivity (W m^{-1} K^{-1})	0.66	0.65	0.64	0.63	0.72	0.61

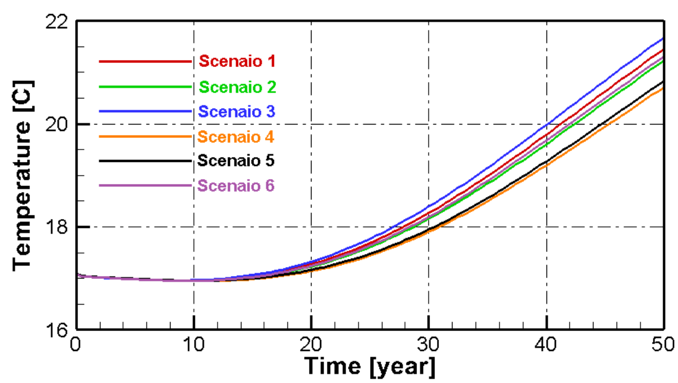

Figure 9: T_{pw} over time for a few different pillar/room sizes.

4.5 Impact of Host Rock Thermal Conductivity

As mentioned earlier, the thermal arrival time and T_{pw} at the production well are determined by how much heat is lost to the host rock. Previously, Doughty et al. (2024) calculated the thermal penetration depth in the host rock is 68 m at 30 years. Using the same properties, the thermal penetration depth is 88 m at 50 years. The host rock thermal property is expected to have a large impact on heat loss, and therefore, the T_{pw} at the production well.

A thermal conductivity of 3.25 W m^{-1} K^{-1} is used for the host rock in the base case scenario. Figure 10 shows the T_{pw} at the production well if the thermal conductivity were 2.1 W m^{-1} K^{-1} instead. A modest temperature increase (2°C at 50 years) is observed.

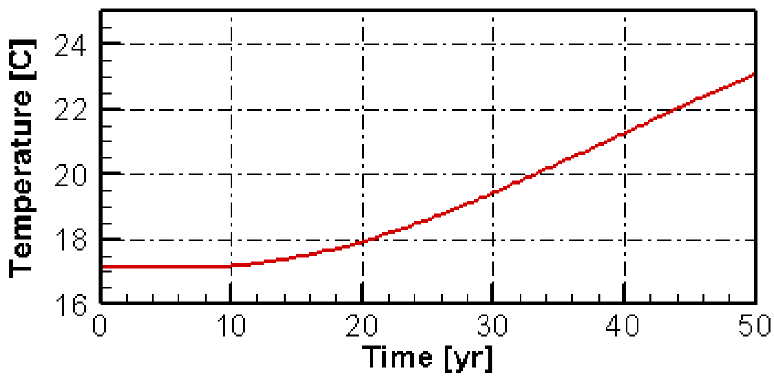

Figure 10: T_{pw} over time for a case with a host rock thermal conductivity of 2.1 W m^{-1} K^{-1}.

To review the factors studied, it seems the geometry and connectivity of the target coal seam has a dominant effect on the T_{pw} . Both host rock thermal conductivity and groundwater flow velocity are also influential factors on the system thermal evolution. The size of pillar/room does not have a much impact given the length and time scale of the system.

5. CONCLUSIONS

The purpose of the Geobattery, to recycle waste heat by storing and transporting it to downstream users through flowing water underground, has potential to be a sustainable clean heating solution. Abandoned underground mine workings could provide connected flow paths for geobatteries, and therefore are good candidates for this operation. This study conceptualized the proposed G2C project into a simplified system and investigated the potential thermal performance for the system using numerical models. There is a large uncertainty regarding the system geometry, connectivity, and properties. Using the same system setup, model variations studied produced very similar results, with minor differences that can be ignored compared to other uncertainties. The subsequent analysis points out that the properties affecting the system are mainly effective permeabilities of the mine workings, the thermal conductivity of the host rock, groundwater flow velocity and most importantly, the geometry (extent of the PR system) and connectivity of these workings. Therefore, it is essential to perform corresponding field tests (e.g., thermal tests, tracer tests) to have a better understanding of the system, and to analyze monitoring data as soon as they are available. With a better understanding of the system, one can decide if other application/operation alternatives should be considered, e.g., adding additional waste heat sources, or identifying closer users downstream.

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