

A scenario-based framework for characterising subsurface uncertainties in shallow mine thermal flow systems

Adetomiwa Aderemi

aa2142@hw.ac.uk

Heriot-Watt University

Elli Maria Charalampidou

Heriot-Watt University

Vasily Demyanov

Heriot-Watt University

Denis Voskov

Delft University of Technology

Research Article

Keywords: Mine-water, Characterisation, Open-Loop, Thermal-Hydraulic, Simulation

Posted Date: September 28th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10932602/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

A scenario-based framework for characterising subsurface uncertainties in shallow mine thermal flow systems

Adetomiwa Aderemi^{1*}, Elli Maria Charalampidou¹,
Vasily Demyanov¹, Denis Voskov²

^{1*}Institute of GeoEnergy Engineering, Heriot-Watt University,
Edinburgh, EH14 4AS, United Kingdom.

²Department of Geoscience & Engineering, TU Delft, Delft, P.O. Box
5048, 2600 GA Delft, Netherlands.

*Corresponding author(s). E-mail(s): aa2142@hw.ac.uk;

Abstract

Repurposing abandoned coal mines for low-carbon heat supply offers significant potential for heat decarbonisation but is hindered by uncertainties in subsurface geology and legacy underground mine-engineering architecture. We present a scenario-based modelling framework for quantifying the impact of these uncertainties on the performance of open-loop mine-water thermal systems with cold-water re-injection. Leveraging data from the Glasgow UK Geoenergy Observatory, we constructed multiple conceptual models with mixed extraction-type configurations and different levels of mine-void connectivity. Flow and heat-transport pathways within and between mine workings were modelled as distinct hydraulic facies, including water-filled voids, backfill lithology, and host-rock heterogeneity. Petrophysical properties were explicitly represented in 3D numerical grids and simulated using the open-DARTS multiphysics simulator.

Our results show that deliverability is governed primarily by the extent of hydraulically connected open voids between an injector and producer, and the influence of backfill becomes significant only when it intersects the principal flow pathway between the wells. When storage capacity is held constant in a low-porosity, low-permeability confining host-rock case, variations in mine connectivity alone reduce thermal lifetime by roughly twenty-fold for a productivity loss of only about 13 per cent. In contrast, a more porous and permeable confining host rock can extend thermal life through conductive heat recharge and pumping-induced advective inflow from connate water in the surrounding aquifer, particularly where mine connectivity is limited.

These findings demonstrate that the volume of hydraulically swept and connected void space is a dominant control on long-term mine thermal-hydraulic performance, rather than merely the total stored heat resource, and highlight the importance of incorporating uncertainties in mine-working architecture when assessing resource potential and project risk.

Keywords: Mine-water, Characterisation, Open-Loop, Thermal-Hydraulic, Simulation

1 Introduction

The UK has long demonstrated that mine-water geothermal energy holds significant promise as a viable pathway for heat decarbonisation. However, despite this potential, widespread deployment has been constrained by a range of scientific and technological challenges that undermine confidence in the long-term reliability of such systems (UKGEOS 2025; Gonzalez Quiros et al. 2025). Many of these challenges arise from uncertainties within the subsurface conditions. Hydrogeological uncertainties are especially consequential: open-loop systems may experience rapid declines in water temperature or flow due to resource depletion (Hall et al. 2011; Receveur 2024), while backfill volume, composition and property contrasts further affect void stability and flow (Brook 1994; Yang 2016). Together, these complexities hinder thermal-hydraulic modelling and introduce risks such as unpredictable flow paths that must be carefully considered when re-engineering design and operation for geoenergy applications.

Accurately forecasting groundwater behaviour in abandoned coal mines remains difficult (Bodeux et al. 2017), in part because geophysical imaging of excavated voids is rarely available. Recent stakeholder engagement in Scotland highlights that improved geoscience understanding is essential, not only for technical system design but also for building public trust, regulatory confidence, and investment certainty throughout project development (Deeming et al. 2024). Despite this, integrating interdisciplinary datasets across spatial and temporal scales to predict heat transport, storage, and recovery efficiency continues to present major challenges (Adams and Younger 2001; Loredó et al. 2016; Walls et al. 2021; Perez Silva et al. 2022).

A substantial knowledge gap persists in how subsurface uncertainties influence quantitative forecasts of mine-water geothermal performance over operational timescales relevant to UK geoenergy networks (Adams et al. 2026). Earlier research (Younger and Robins 2002; Renz et al. 2009; Brouyère et al. 2009; Hamm and Bazargan Sabet 2010) highlighted the importance of predictive post-closure modelling for environmental management. Traditional assessments often rely on simplified analytical methods or 2D models with deterministic parameters, whereas mine-aquifer systems involve complex, physically coupled processes shaped by subsurface heterogeneity that are more accurately represented in 3D (Loredó et al. 2016; Kallesøe and Vangkilde-Pedersen 2019; Orban et al. 2024). Robust conceptual models are therefore essential for characterising void connectivity (Adams and Younger 2001) and the spatial uncertainties that influence heat recovery within mineworkings (Ó Dochartaigh 2009; Andrews et al. 2020; Monaghan et al. 2022a,b).

Addressing these challenges requires structured, uncertainty-aware workflows. Scenario-based optimisation studies have linked demand schedules to coupled thermal-hydraulic mine simulations, for a proposed district heating and cooling network in Canada (Raymond and Therrien 2014) and, with co-simulation of surface-facility design, for the Ruhr-University Bochum campus (Spengler et al. 2025).

Recent advances in 3D mine-water modelling highlight the trade-off between computational efficiency and the ability to quantify uncertainty. The GEMSToolbox (Mouli-Castillo et al. 2024) enables rapid feasibility screening by representing mine galleries as pipe networks coupled with analytical heat-transfer solutions, but cannot explicitly resolve the vertical heterogeneity and lateral continuity of sequences that characterise many mined environments. The importance of capturing geological uncertainty is underscored by Perez Silva et al. (2022), who showed that a 2-metre variation in coal-seam thickness produced a 163% difference in thermal-storage capacity, illustrating the systematic bias that arises from limited characterisation data. Differing assumptions about mine-water storage volumes likewise lead to markedly different thermal predictions (Guo et al. 2023). Beyond thermal applications, González Quirós and Fernandez (2019) demonstrated that 3D finite-element modelling of complex flooded mine networks is computationally tractable, performing Monte Carlo uncertainty analysis with coupled continuum-pipe-flow methods, though focused on environmental management in the Spanish Asturian Coal Basin.

Coupled thermal-hydraulic-mechanical (THM) studies have begun to address mine stability during mine-water-based thermal production and injection. Todd et al. (2024) showed that operational parameters, such as injection temperature and water level, exert a stronger influence on shallow-mine stability than geological conditions, while Zhang et al. (2025) applied Distance-based Generalised Sensitivity Analysis (DGSA) across stochastic 2D simulations of deep geothermal mine systems, identifying mine location, injection parameters, and mechanical properties as dominant controls. These 2D approaches cannot fully capture the confining layer heterogeneity and coupled interactions inherent in 3D mine geometries, where property distributions and backfill materials vary significantly in space.

Recent assessments (UKGEOS 2025; Adams et al. 2026) highlight key technical barriers limiting UK geothermal and aquifer thermal energy storage (ATES) deployment. These include mine characterisation, upscaling, long-term coupled thermal-hydraulic-mechanical (THM) responses, and thermal interference between overlapping schemes. Given the operational parallels between ATES and mine-water geothermal systems, the geological heterogeneity of UK aquifers underscores the need for high-resolution coupled thermal-hydraulic models. Motivated by this gap, our study characterises the single-phase thermal-hydraulic behaviour of an abandoned, fully water-saturated coal mine to evaluate its potential for low-enthalpy geothermal energy extraction.

This study investigates two key research questions. First, do spatially dependent factors (such as mine geometry, backfill, void distribution, and host-rock properties) influence hydraulic deliverability and thermal longevity in the same way? Second, what primarily governs a system’s thermal lifetime: the total heat stored within the workings, or only the connected heat swept by the operating wells?

To answer these questions, we integrate a ‘Shared Earth’ modelling workflow with the open-source open-DARTS multiphysics simulator [Voskov et al. \(2024\)](#), calibrating models using pumping-test data, core samples, and borehole logs from the UKGEOS Glasgow facility. Incorporating historical mine plans and equiprobable parameter distributions, we simulate an ensemble of equally plausible subsurface realisations to capture geological uncertainty. Through scenario-based modelling, we demonstrate how these forward simulations link site-specific subsurface responses to long-term performance expectations for heterogeneous, open-loop mine-water geothermal systems with reinjection.

This approach adapts to mine workings a geothermal simulation capability established for conventional reservoirs, where open-DARTS has been applied to low-enthalpy doublets in heterogeneous sedimentary formations ([Chen et al. 2025](#)) and to high-enthalpy fractured systems ([Wang et al. 2021](#)). The physics required for a flooded mine is the same single-phase thermal formulation used in those studies. What is specific to the mine is the geometry, in which the permeability contrast between open voids and host rock takes the role that the fracture-matrix contrast plays in fractured reservoirs.

2 Methods

2.1 Study Site and Data

The Glasgow UK Geoenergy Observatory (UKGEOS) is located in Rutherglen, South Lanarkshire, on the eastern urban area of Glasgow, United Kingdom ([Starcher et al. 2021](#)). Geologically, the site lies within the Coal Measures Group of the Central Midland Valley of Scotland. The facility provides openly accessible datasets, comprising of 12 boreholes distributed across 5 surface sites. Four sites are located main within the Cuningar Loop Park, with the exploratory borehole GGC01 located at a separate Dalmarnock site, 1.5 km west of the main cluster. The facility was made available to the research community in December 2020 ([British Geological Survey 2020](#)), offering comprehensive monitoring capabilities through several sensors installed at depth ([Monaghan et al. 2022a,b](#)).

We used pre-built mapped horizon surfaces, fault surfaces, depth-to-base grids, and borehole well tops from the published post-drill bedrock and mine model data ([Kearsey and Burkin 2021a](#)) to build our Geomodel. Additional information is available in a series of open reports ([Monaghan et al. 2019, 2026](#)).

Multi-sensor core logger (MSCL), optical images, X-ray computed tomography images of borehole core, and laboratory analyses on cores enhanced the 3D model workflow through high resolution characterisation of host rock lithofacies and unworked coals at the exploratory borehole site ([Beynon 2020](#); [Payton et al. 2021](#); [Chandler et al. 2023](#); [Charalampidou et al. 2023](#)) similar to the method described in [Smith et al. \(2020\)](#). We achieved core-to-log integration following depth-shift procedures from [Monaghan et al. \(2021\)](#). Wireline logs, together with the core analysis, were integrated to derive representative petrophysical parameters. Borehole electrofacies were defined using shale-volume estimates, porosity derived from density, sonic logs and colour-inverted acoustic image arrays. Our correlations were compared to existing rock

chip descriptions collected during drilling, and post drill depositional environment interpretations (Monaghan et al. 2021).

Evidence of collapsed roof rock (goaf) and potential backfill was synthesised from these datasets alongside borehole optical images, and drill cutting logs. Field-scale estimates of mine void permeability were constrained using preliminary interpretation of baseline hydrogeological aquifer test pumping data (Shorter et al. 2021).

2.2 Classification of Uncertain Factors

Not all uncertain factors exert equal influence on the coupled thermal-hydraulic response of a flooded coal mine; treating them uniformly in an ensemble needlessly inflates computational cost while obscuring dominant controls. We therefore classify the eight uncertain factors examined in this study using a two-tiered decision workflow shown in Figure 1.

Tier 1 (host-rock permeability: sealed Scenario (S1) vs. leaky Scenario (S2)) and Tier 2 (mine geometry configurations) establish the nested scenario context (Sections 2.3 and 2.5). Within this context, individual parameters are split into two groups. Group I factors (comprising mine geometry, backfill volume, backfill properties, and void properties) interact with the internal mine architecture to produce non-linear, geometry-dependent flow patterns requiring full 3D coupled simulation. Conversely, Group II factors (operating controls, rock compressibility, thermal gradient, and pressure gradient) serve as boundary or background parameters whose effects follow established analytical relationships; these are held at reference values across the ensemble (Section 2.4).

2.3 Mine Model Framework

To investigate the coupled thermal-hydraulic response across the worked-area boundary for a representative mine, we developed a set of idealised model configurations, assuming laterally extensive and continuous coal facies over the Glasgow Main Zone. We conceptualised multiple mine configurations representative of a combination of room-and-pillar and longwall geometries typical of some abandoned UK coal mines, with variations in pillar dimensions, connected void volumes, backfill extent and associated hydraulic properties, to capture uncertainty in flooded mine galleries within the context of the Glasgow UKGEOS hydrogeological conceptual model (Gonzalez Quiros et al. 2024).

In our conceptualisation, the flooded mine galleries function as high-permeability conduits embedded within lower-permeability host rock layers, forming a dual-domain system with contrasting hydraulic properties. Interactions between the mine voids and surrounding host rock can occur through: (1) vertical connectivity via high-porosity, high-permeability confining layers linking galleries to overlying strata and (2) lateral continuity or the lack of same; through mine gallery-bounded flow pathways, collapsed rubble zones (or goaf), and backfill (mine waste) zones within the workings.

Multiple vertically stacked coal seams were encountered by the GGC01 borehole, with lithologies including intercalated siltstones, organic-rich mudstones, palaeosols, and fluvial-marine sandstones (Monaghan et al. 2021). To balance model complexity

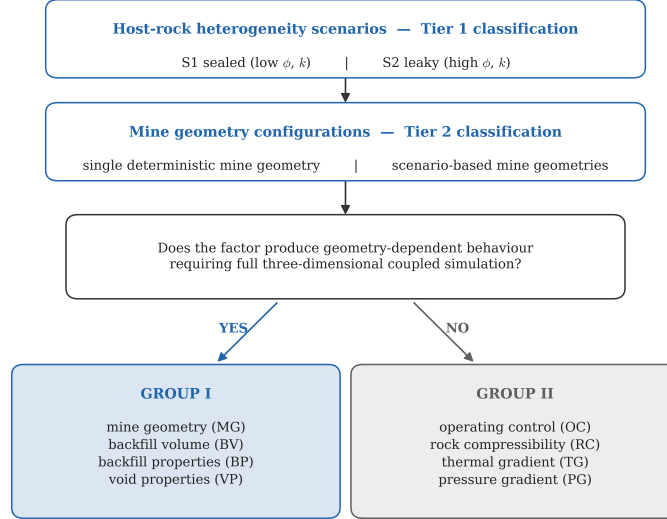


Figure 1: Decision workflow for classifying the eight uncertain factors within a two-tiered scenario framework. Group I factors are resolved using 3D coupled simulation, whereas Group II factors are held at reference conditions (Section 2.4; Appendix A). Material-property variations are evaluated via 13 one-at-a-time (OAT) parameter sweeps across six representative mine geometries (Figure 4), executed under both host-rock scenarios (S1 sealed vs. S2 leaky) to yield a 176-run ensemble.

with computational cost while still capturing key thermal-hydraulic processes, we constrained the model domain to 5 stratigraphic zones, consisting of 10 hydraulic facies. (Figure 2).

Mine void-host rock interactions are represented through the two end-member host-rock scenarios of Figure 1, a framework of interpretational bias. Scenario 1 is based on density-derived porosity, reflecting intact, matrix-dominated, low porosity, confining units of a 'well-sealed' working in which the thermal-hydraulic response is largely confined to the mine void network, while Scenario 2 is based on sonic-derived porosity, and conceptually represents enhanced vertical connectivity enabled by fractures at the mine void-host rock interface, or preferentially oriented multiple fracture clusters within heteroliths in dipping confining layers (Pettigrew et al. 2026) – a 'leaky' system in which vertical exchange with the overlying strata governs long-term thermal storage and recovery. Furthermore, Charalampidou et al. (2023) also showed preferential water migration through sub-vertical fractures intersecting horizontal laminations in a tidal sandstone sample from GGC01. Permeability values for non-coal hydraulic facies were derived using a Wyllie-Rose transform (Wyllie and Rose 1950), which relates permeability to total porosity and irreducible water saturation through lithology-specific empirical coefficients (Timur parameters; Timur 1968). Most of the S1 density-derived values align with core interpretation from different authors (Beynon 2020; Payton et al. 2021; Chandler et al. 2023) (Figures 2 and 3), while S2 samples are at least two orders of permeability magnitude higher than S1, typical of enhanced fracture-flow

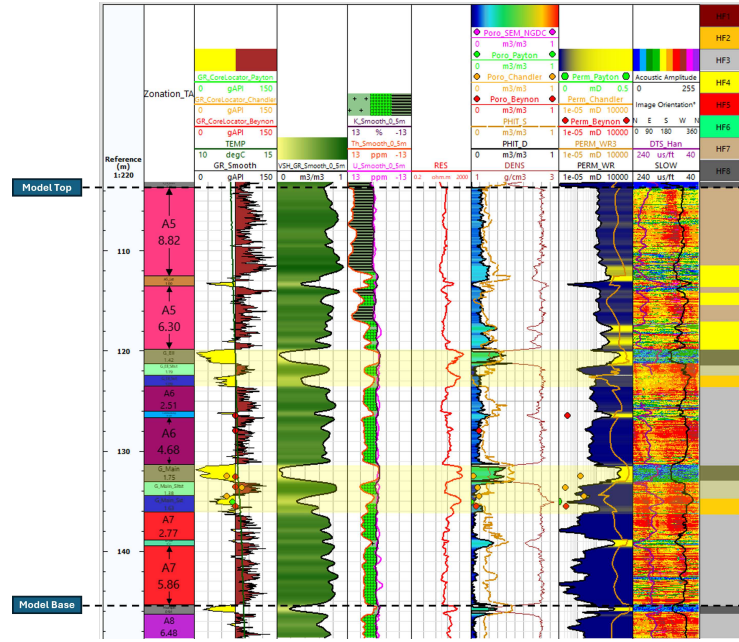


Figure 2: GGC01 wireline log analysis. Vertical extent of the geomodel domain is from the roof above Glasgow Ell Coal down to the floor underlying the Glasgow Main Coal working.

behaviour observed in shallow Midland Valley aquifers (Gillespie et al. 2013; Kearsey et al. 2024). The facies property values used in the 3D model are listed in Appendix A. The resulting spatial distribution of permeability along the injector–producer section, for both host-rock scenarios, is shown later in Figure 13, where it is set against the thermal response it produces (Section 3.4).

2.4 Reference Conditions

A reference model, G1400B, represents the conceptual worked area of the South-Eastern (SE) coal extraction block, with an idealised doublet configuration of vertical producer (PRD12) and injector (INJ12), separated by 435 m. The producer abstracts ambient mine water at a constant rate of $1660 \text{ m}^3 \text{ d}^{-1}$, while the injector returns thermally spent water at 6°C with the same rate, giving a balanced, voidage-neutral circulation. The initial state is set by a hydrostatic pressure gradient of 98.1 bar km^{-1} and a geothermal gradient of 30°C km^{-1} within similar ranges found in Abesser (2010); Gillespie et al. (2013); Receveur et al. (2020); Farr et al. (2021); Kearsey et al. (2024). Rock compressibility is held at 0.01 bar^{-1} , representing shallow, partially lithified, fluvial sequences (Freeze and Cherry 1979) and the cleat compressibility of worked coal of laboratory and in-situ well-test measurements span approximately $4 \times 10^{-3} \text{ bar}^{-1}$ to $3 \times 10^{-1} \text{ bar}^{-1}$ about a central value near $2 \times 10^{-2} \text{ bar}^{-1}$ (Seidle 2011; Taco et al. 2020). A single compressibility is applied to every lithology, so the same value also governs pore-volume change in the confining strata, where consolidated sandstones and mudstones would be appreciably stiffer. The consequences of

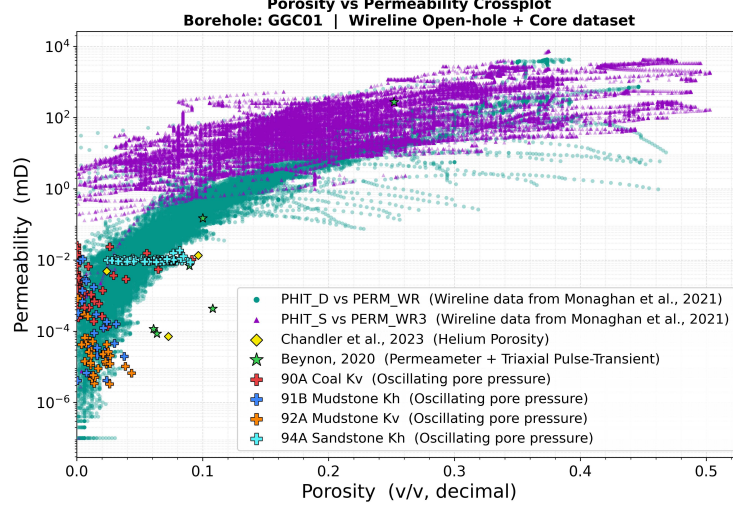


Figure 3: Porosity–permeability crossplot for borehole GGC01, combining wireline open-hole and core datasets from [Monaghan et al. \(2021\)](#); and overlays from core analyses in [Chandler et al. \(2023\)](#) (helium porosity and oscillating pore-pressure permeability) and [Beynon \(2020\)](#) (permeameter and triaxial pulse-transient permeability).

this simplification are discussed in Section 4.3. The resulting pore-volume response to circulation ($\Delta V \approx cV \Delta p$), and its coupling to operational strategy (e.g. mine thermal energy storage) or to backfill rheology, is not explored here. This doublet placement and rate balance are chosen so that the pumped pressure response propagates through the worked-out voids from producer to injector across the dip-closed Glasgow Main Coal structure, establishing the inter-well flow field that the scenario ensemble (Section 2.5) modifies. The mine working is modelled initially with no emplaced backfill. This open-void condition, identified by the case suffix (BV1_BP3_VP3), was used to analyse the results of mine geometry uncertainty in Section 2.5. Backfill, together with its own properties, is introduced as a Group I material uncertainty in Section 2.5, where the property sensitivities are characterised about a 15 %-backfill volume, with case run suffix identified by (BV3_BP3_VP3). Thermal properties (conductivity and heat capacity) are assigned by hydraulic facies, are uniform across coal seams in the ensemble, and are identical between the two host-rock scenarios (Appendix A).

2.5 Scenario and Realisation Design

Resolving field-scale 3D fracture networks in abandoned workings requires multi-scale characterisation data that are rarely available. The fracture-enhanced S2 scenario is therefore implemented via effective porosity–permeability relationships rather than explicit 3D fracture modelling. S1 and S2 alter both recovery magnitude and spatio-temporal flow dynamics, so every Group I parameter sweep and mine-geometry realisation is evaluated independently under each host-rock scenario. This keeps scenario-level (interpretational) uncertainty, the S1–S2 contrast itself, distinct from the parameter-level spread within each host-rock scenario.

Mine geometry represents the second tier of epistemic uncertainty, spanning both the scenario and realisation levels of the ensemble hierarchy. Only the confining-layer porosity and permeability change between the low (S1) and high (S2) porosity–permeability host-rock scenarios (Table A3). Within each host-rock scenario, 16 conceptual mine-geometry models of the South-Eastern (SE) coal extraction block are grouped into three structurally distinct geometry configurations (Figure 4). The number of realisations per configuration reflects confidence in available mine-abandonment plans; here, the ensemble deliberately includes end-member models that bracket, and in places slightly exceed, the plausible range.

Three additional Group I parameters capture material-property uncertainty: Backfill Volume (BV), Backfill Properties (BP; porosity–permeability), and Void Properties (VP; porosity–permeability). These parameters are classified as Group I because their thermal-hydraulic impacts are intrinsically coupled to mine geometry. Specifically, how a given backfill volume or void permeability alters inter-well sweep, breakthrough timing, and far-field pressure depends on where that material-property contrast sits relative to preferential flow paths, a spatial dependency requiring 3D coupled simulation.

Backfill and void property sensitivities are evaluated across a representative subset of six mine geometries spanning the spectrum of structural connectivity: one from Scenario A, two from Scenario B, and three from Scenario C (Table A2). Running one-at-a-time (OAT) sensitivity sweeps on this subset is sufficient, as material-property effects vary predictably across each structural group, eliminating the need to execute full parameter sweeps across all 16 models.

The four Group II parameters shown in Figure 1 are held at the reference values detailed in Section 2.4. This design choice does not imply negligible influence; rather, it acknowledges that their first-order impacts follow well-understood hydrogeological and thermodynamic principles, making additional coupled simulation runs redundant.

2.6 Numerical Model Implementation

Simulations were performed using open-DARTS (Delft Advanced Research Terra Simulator), an open-source finite volume multiphysics simulator employing Operator-based linearisation (OBL) to efficiently solve non-linear conservation equations (Khait 2019). The OBL approach decomposes physical processes into independent state-dependent operators, enabling adaptive re-linearisation during Newton-Raphson iterations and reducing computational expense in regions with weak non-linearities. This modularity is particularly advantageous for coupled thermal-hydraulic problems with sharp property contrasts between mine voids and host rock.

The geothermal physics of the simulator was verified against TOUGH2 and AD-GPRS on a suite of single- and two-phase benchmarks, reproducing reference solutions at reduced computational cost (Wang et al. 2020). Coupled thermal-hydraulic-mechanical processes are supported within the same finite volume framework, in which mass, energy and momentum balances are discretised with multi-point approximations on a single collocated grid (Novikov et al. 2025). That capability is not exercised here, since geomechanics is excluded from the present scope (assumption 5 below), but it

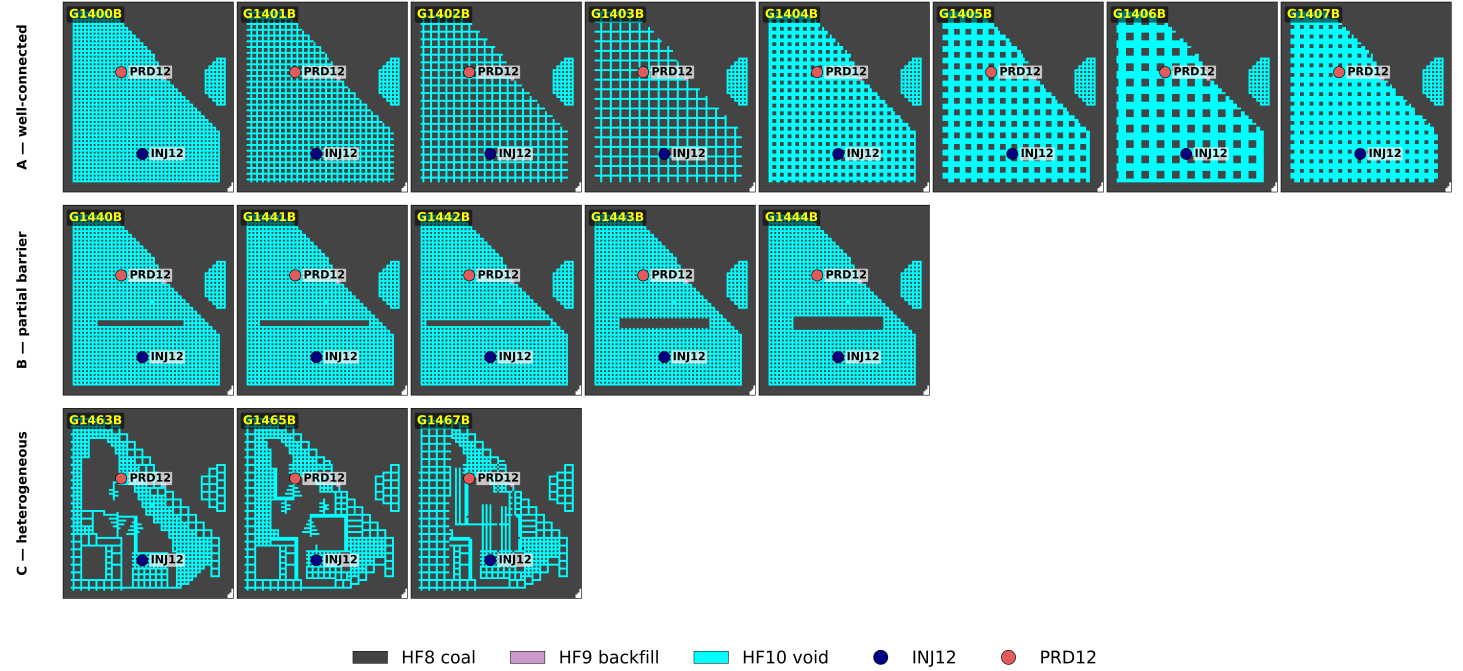


Figure 4: Realisations of the mine-geometry (MG) models, categorised into three scenarios that address the study questions. **Scenario A**, a uniform, well-connected room-and-pillar mesh, varies two geometric controls independently while holding the external mine boundary fixed: the void fraction (extraction ratio f_{void} ; axis A.f), set by resizing the coal pillars (p) and voids (v), and the size of the repeating pillar-and-void unit (the pattern length-scale; axis A.u). **Scenario B**, a focused partial compartmentalisation study on G1400B, progressively varies the degree of constriction through the coal barrier's length (the fraction of the span it covers relative to the external mine boundary) and its width (the barrier extent measured perpendicular to its length), at controlled well spacing (injector and producer placed opposite each other, in equal connected mine volumes on either side of the barrier). **Scenario C**, a mixed-extraction-type, spatially irregular void network (external boundary again fixed), combines variable-dimension room-and-pillar workings, longwall-style panels and local regions of unworked coal; its three realisations share the same static void volume (storage capacity) but differ in mine connectivity

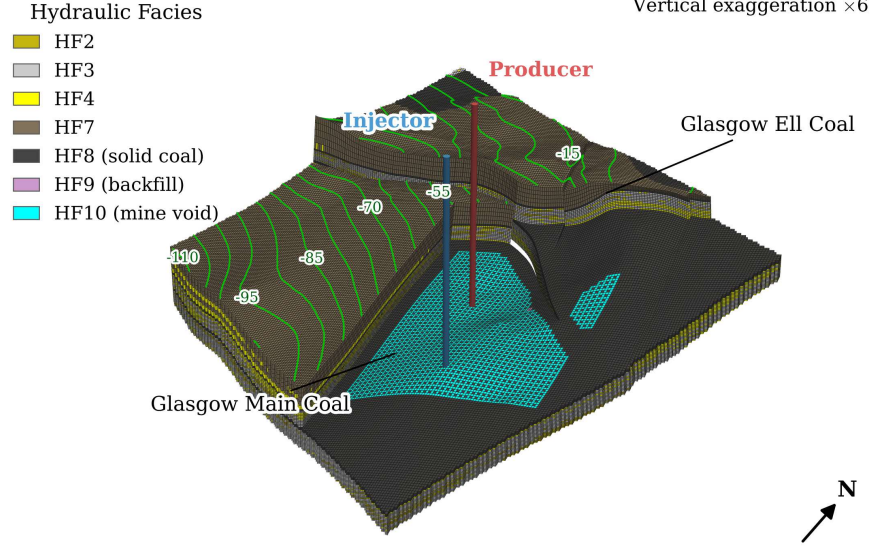


Figure 5: 3D static model grid shown for realisation G1400B.S1.BV1.BP3.VP3. The overburden is cut away over the south-eastern worked area to expose the Glasgow Main Coal working in full, with the Glasgow Ell Coal appearing as the seam on the cut face above. HF2–HF7 are host-rock facies. Green lines are Glasgow Ell Index structural contours at 5 m intervals, labelled in m OD.

is the route by which these models would be extended to the shallow-mine stability questions raised by [Todd et al. \(2024\)](#) and [Zhang et al. \(2025\)](#).

The geothermal engine we used for our model solves coupled single-phase mass and energy conservation equations under non-isothermal Darcy flow conditions with all governing equations derived in [Voskov et al. \(2024\)](#). The 3D model domain was discretised into a structured $260 \times 229 \times 33$ Corner Point Grid with cell dimensions of $10 \text{ m} \times 10 \text{ m}$ (horizontal) $\times 1 \text{ m}$ (vertical), spanning approximately $2.6 \text{ km} \times 2.3 \text{ km} \times 33 \text{ m}$ in the X, Y and Z axes. This balanced computational efficiency with adequate resolution of thermal-hydraulic gradients in room-and-pillar mine void-host rock systems. Each borehole screened interval was validated to ensure that it did not pass through coal pillars and that it was drilled through the centre of a grid cell. The grid cell orientation was aligned with the trends of the conceptual mine geometry (Section 2.5), following the strike and dip directions of the top structure map (Figure 5).

The following conditions and assumptions were implemented to isolate coupled thermal-hydraulic behaviour for low-enthalpy geothermal systems operating at temperatures well below boiling ($\leq 25^\circ\text{C}$ in this study), where phase change is not anticipated. Boundary conditions are specified as follows:

1. Lateral boundaries: no-flow conditions for mass and heat
2. Top boundary: fixed temperature corresponding to mean surface temperature
3. Bottom boundary: fixed temperature based on geothermal gradient
4. Chemical reactivity: no rock-fluid interaction or mineral dissolution/precipitation

5. Geomechanics: no stress-dependent permeability or coupled thermal-hydraulic mechanical interactions

All simulations were run for 4,380 days (12 years) to capture meaningful thermal lifetime behaviour while maintaining computational efficiency and data storage feasibility. This duration represents a conservative lower bound for mine-water heat project amortisation periods, which typically span up to 20 years (Banks et al. 2009; Greening and Azapagic 2012; Sevindik et al. 2021). Fixed time steps of 30 days over 146 steps were employed for continuous operation, with adaptive time-stepping capabilities especially useful for future cyclic loading investigations.

Fluid density and viscosity are evaluated dynamically throughout the simulation domain using the International Association for the Properties of Water and Steam formulations – IAPWS-IF97 for thermodynamic properties (Wagner and Kruse 1998) and the IAPWS 2008 Release for viscosity (International Association for the Properties of Water and Steam (IAPWS) 2008) - both implemented within open-DARTS as property evaluator modules. At each timestep, the local thermodynamic state of each grid cell, defined by pressure (P) and specific enthalpy (h) as primary variables, is mapped to the appropriate IAPWS-IF97 thermodynamic region, from which density is computed as the inverse of specific volume and viscosity as a function of the resulting local temperature and density. These formulations were first coupled to open-DARTS for reservoir-scale geothermal modelling, where pressure and specific enthalpy were adopted as primary variables and the IAPWS-IF97 property evaluation was parameterised in that state space through OBL (Khait and Voskov 2018).

Under low-enthalpy conditions within Glasgow-UKGEOS (at temperatures $\leq 25^\circ\text{C}$, and depths $\leq 500\text{ m}$), all 3D grid cells remain in region-1 in the phase envelope, ensuring a physically consistent and thermodynamically coupled property field. Consequently, the temperature dependence of viscosity is continuously captured across the domain (ranging from approximately 1.30 mPas at 10°C down to 0.89 mPas at 25°C), rather than an assumed constant value. Well flow rates specified under volumetric control (WRATE) are converted to mass rates at each timestep using the density evaluated at the well cell’s local (P, h) state, such that the effective mass flux evolves dynamically with subsurface conditions.

2.7 Performance Metrics and Analysis Approach

Although several performance metrics can be derived from a simulation, the analysis in this study is carried by two: the productivity index (PI), a hydraulic measure of well-to-well flow resistance (Section 2.7.1), and the thermal production lifetime (TPL). Three further thermal metrics, namely useful thermal energy, useful thermal power and the thermal recovery factor, are reported for the baseline case only and are defined in Section 2.7.3. Pressure was tracked alongside the thermal metrics: bottom-hole pressure changes and the injector–producer differential were monitored at each timestep to assess hydraulic communication as gradients evolved. The following concepts are first defined below before being applied in the derivation of these metrics.

2.7.1 Hydraulic Communication

Hydraulic communication between the doublet boreholes is quantified directly from the simulated bottom-hole pressures (BHP). The inter-well pressure differential is the quasi-steady, late-time pressure difference that drives circulation from injector to producer:

$$\Delta p = \overline{\text{BHP}}_{\text{INJ}} - \overline{\text{BHP}}_{\text{PRD}}, \quad (1)$$

where each bottom-hole pressure is averaged over the final $\sim 20\%$ of timesteps (the quasi-steady late-time window). Under the constant-rate reference control (WRATE; Section 2.4), the circulation rate Q is prescribed and identical across cases, so Δp is the direct physical measure of inter-well flow resistance. Under the alternative bottom-hole-pressure control (WBHP), which instead holds the injector–producer pressure pair fixed, that same resistance manifests as a decline in circulation rate rather than a rise in Δp .

The corresponding deliverability is measured by the productivity index (PI),

$$\text{PI} = \frac{Q}{\Delta p}, \quad (2)$$

expressed in $\text{m}^3 \text{day}^{-1} \text{bar}^{-1}$, where Q is the steady state producer rate and Δp is the inter-well pressure differential. Deliverability controls how readily water circulates between injector and producer and is set by the open cross-sectional area linking the boreholes: the width and continuity of the inter-well flow path. A higher PI denotes a better-connected doublet that sustains the prescribed circulation rate at a smaller pressure differential, and hence at lower pumping head and hydraulic cost; because Q is fixed, $\text{PI} \propto 1/\Delta p$. This definition is the reservoir engineering analogue of aquifer specific capacity, C_s , the well discharge per unit drawdown (Freeze and Cherry 1979, p. 332). The productivity index is the primary connectivity metric distinguishing Scenario C realisations (Section 2.5), which share a common static void volume but differ in the fraction of that void hydraulically connected to the boreholes.

Both the differential Δp and PI characterise the quasi-steady, late-time pressure field. Distinct from these is the transient bottom-hole-pressure response: the early-time pressure drawdown at the producer and buildup at the injector as the field establishes over the first weeks of circulation. This transient reflects near-well storativity and the degree of host-rock hydraulic communication rather than the steady inter-well flow resistance, and is used in that role to distinguish the sealed (S1) and leaky (S2) host-rock scenarios (Section 3.4).

2.7.2 Thermal Production Lifetime

Two complementary thermal metrics are tracked from the producer temperature history, the thermal breakthrough time (TBT) and the thermal production lifetime (TPL), using two temperature criteria that mark the progression of the cold front:

1. **Primary criterion (early warning):** we selected 0.5°C as the first detectable temperature decline from the initial production temperature, to indicate thermal

front arrival. The temperature decline rate directly reflects thermal breakthrough progression.

2. **Economic limit:** according to [Falcone et al. \(2017\)](#), is defined as:

“the time at which the project reaches a point beyond which the subsequent cumulative discounted net operating cash flows or financial benefit from the project would be negative.”

For a geothermal energy project, the economic limit may be the time when the expected extraction rate declines to a level that makes the project uneconomic, or when it is uneconomic to invest in further project infrastructure, refurbishment, or maintenance of existing equipment, such as additional wells or treatment systems for the geothermal fluid ([Falcone et al. 2017](#)).

The first criterion defines the TBT and marks thermal-front arrival, while the second governs t_{cutoff} and hence the TPL. In this study, t_{cutoff} corresponds to the time at which the produced water temperature falls to 10 °C, beyond which mine-water thermal extraction is considered uneconomical. This economic limit is also the abandonment temperature to which the recovery factor is referenced in (Section 2.7.3).

Thermal longevity, measured by the thermal production lifetime (TPL), is the duration from operational start until the produced temperature reaches that economic limit, and is set by how much heat-bearing mine void the circulating water actually sweeps along the way. It therefore bounds the window for useful thermal energy extraction. TPL is governed here by the temperature cutoff alone. In a real scheme the viable duration would also be bounded by a maximum allowable inter-well pressure differential, equivalently a maximum drawdown, which additionally sets the required pump work, and by the project amortisation or contract period.

2.7.3 Supplementary Thermal Metrics

Three further metrics are reported for the baseline case only (Section 3.1). The heat delivered at the wellhead follows the standard thermogeological yield relation ([Banks 2012](#); [Walls et al. 2021](#)), integrated only over the economically viable period, that is, up to the t_{cutoff} defined in Section 2.7.2 ([Oppelt et al. 2025](#)):

$$E_{\text{useful}} = \int_0^{t_{\text{cutoff}}} C_{V,w} Q(t) [T_{\text{producer}}(t) - T_{\text{injection}}] dt, \quad (3)$$

where $C_{V,w} = \rho_w C_{p,w}$ is the volumetric heat capacity of water, evaluated through the IAPWS-IF97 formulation ([Wagner and Kruse 1998](#)), $Q(t)$ is the circulation rate and $T_{\text{injection}} = 6$ °C (Section 2.4). The useful thermal power is $P_{\text{useful}} = E_{\text{useful}}/t_{\text{cutoff}}$, the mean rate sustained while production remains above the cutoff, and the figure relevant to sizing surface heat-delivery infrastructure ([Banks et al. 2009](#); [Walls et al. 2021](#)). Taking the same integral over the full simulation gives the total extracted energy E_{total} and the average power $\bar{P}_{\text{avg}} = E_{\text{total}}/t_{\text{sim}}$, where t_{sim} is the full 4380 d (12-year) simulation period. Both include post-cutoff production, so E_{total} exceeds E_{useful} and bounds total extraction rather than economically usable yield, whereas $\bar{P}_{\text{avg}}$ spreads that energy over the full simulation period and is correspondingly lower

than P_{useful} . Raising the circulation rate increases instantaneous power but accelerates breakthrough and shortens the viable period (Gringarten 1978).

The thermal recovery factor follows the volumetric “heat in place” convention (Muffler and Cataldi 1978), in the reformulation of Garg and Combs (2015):

$$\begin{aligned}\eta_{\text{recovery}} &= \frac{E_{\text{rec}}}{E_{\text{static}}}, \\ E_{\text{rec}} &= \int_0^{t_{\text{cutoff}}} C_{V,w} Q(t) [T_{\text{producer}}(t) - T_{\text{cutoff}}] dt, \\ E_{\text{static}} &= \sum_r [\phi_r C_{V,w} + (1 - \phi_r) C_{V,s,r}] V_r (T_{\text{initial}} - T_{\text{cutoff}}),\end{aligned}\tag{4}$$

Garg and Combs (2015) show that referencing recoverable heat to an arbitrarily low temperature, such as the ambient or reinjection temperature, yields an optimistic estimate, and that the abandonment temperature should be used instead. The two numerators therefore answer different questions: E_{useful} is what the producer supplies at the wellhead, the quantity relevant to sizing surface plant, whereas E_{rec} is the fraction of the resource recovered. The subscripts denote the water (w) and solid rock-matrix (s) phases; the index r runs over the thermally affected regions, namely the mine voids, coal pillars and backfill within the worked block, and the surrounding confining strata. For each region, V_r is the bulk volume, ϕ_r the porosity and $C_{V,s,r}$ the volumetric heat capacity of its rock matrix, the latter two taken as effective (volume-averaged) values. The bracketed term is the bulk volumetric heat capacity of region r , combining its pore water and its matrix. Region properties defined in Table A3 carry uncertainty, so E_{static} is evaluated as a central estimate across their stated ranges.

3 Results

3.1 Baseline Performance Behaviour

The model introduced in Section 2.4 (G1400B.S1.BV1.BP3.VP3) serves as a baseline against which subsequent mine-geometry realisations are benchmarked. Parametric material-property iterations discussed in (Section 3.3) are centred on the 15%-backfill volume case identified by the suffix (BV3.BP3.VP3).

Under constant-rate circulation at $1660 \text{ m}^3 \text{ d}^{-1}$, the doublet establishes a quasi-steady pressure field within the first few weeks of operation (Figure 6a). Injector and producer bottom-hole pressures stabilise at a late-time inter-well pressure differential of $\Delta p \approx 0.45 \text{ bar}$ (Equation 1), corresponding to less than 5 m of hydraulic head loss across the 435 m doublet spacing. The resulting productivity index, $\text{PI} \approx 3690 \text{ m}^3 \text{ d}^{-1} \text{ bar}^{-1}$ (Equation 2), is reasonably high, confirming that the baseline behaves as a single, near-frictionless, highly well-connected reservoir sustaining the target rate at minimal drawdown.

This high hydraulic connectivity, however, causes early thermal breakthrough. Producing initially at 12.4°C , the well cools by 0.5°C after a thermal breakthrough time of $\text{TBT} \approx 215 \text{ d}$ (Figure 6b, inset) and falls to the 10°C economic cutoff at a thermal

production lifetime of TPL ≈ 1225 d (≈ 3.4 years; Figure 6b). Production temperature thereafter declines more slowly, reaching 8.3°C at 12 years and remaining well above the 6.0°C reinjection temperature. Heat conducted from the confining strata sustains the producer long after the connected void network itself has been swept. This baseline case thus pairs high hydraulic deliverability with moderate thermal longevity, and serves as the benchmark against which the geometry and material-property ensembles are compared.

Over the 12-year simulation period, the producer extracts approximately 29 800 MW h of total thermal energy relative to the reinjection temperature. The useful thermal energy delivered above the 10°C cutoff is 11 700 MW h, at an initial peak useful power of ≈ 510 kW falling to a mean of ≈ 400 kW over the thermal production lifetime. The doublet recovers under a tenth of the heat stored in the volume it contacts, with a thermal recovery factor (Equation 4) of $\eta \approx 0.08$; the remainder is left behind by thermal short-circuiting through the connected void network.

PI and TPL are set by the subsurface and wellbore response alone, so they provide robust, surface-independent indicators of hydraulic deliverability and thermal longevity across the full model ensemble (Section 2.7).

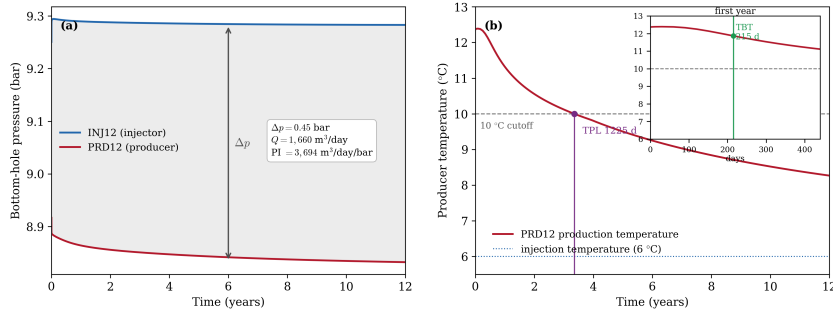


Figure 6: Reference-case (G1400B.S1.BV1.BP3.VP3) model response over the 12-year simulation. (a) Injector (INJ12) and producer (PRD12) pressures. (b) Producer temperature, with the thermal breakthrough time (TBT) and thermal production lifetime (TPL) zoomed-in on the first-year inset.

3.2 Mine Geometry Controls on Performance

Three scenario groups discussed in Figure 4 isolate the impact of internal mine architecture on energy performance: bulk void fraction (Scenario A), partial flow barriers (Scenario B), and mine connectivity at fixed storage capacity (Scenario C).

Deliverability and thermal lifetime both increase with void fraction in the well-connected Scenario A models, but neither is controlled by it alone (Figure 7a). Across the tested range ($f_{\text{void}} = 0.40\text{--}0.86$), PI rises near-monotonically by a factor of ≈ 3.2 , from 1470 to 4750 m³ d⁻¹ bar⁻¹, as an increasingly open gallery network widens the inter-well flow cross-section and reduces tortuosity. TPL still rises more steeply: at a fixed room width of 10 m it lengthens from 330 to 1225 d between $f_{\text{void}} = 0.40$ and 0.76 (G1403B to G1400B). The temperature fields show the two end-members directly,

cooled water accumulating as a dense plume around the injector at high extraction (Figure 8a) but confined to narrow galleries between large coal pillars at low extraction ratio (Figure 8b).

A second control acts independently of void fraction. The four realisations at $f_{\text{void}} = 0.758\text{--}0.781$ (G1400B, G1404B, G1405B and G1406B) differ only in the pillar-and-void length-scale, and separate systematically by it: as rooms and pillars coarsen from 10 to 40 m, TPL falls 19 % from 1225 to 990 d while PI rises 28 %. A finer working presents more void-rock interfacial area per unit of stored water, so conductive recharge from the surrounding strata is more effective even where the stored volume is unchanged; coarsening the workings therefore trades thermal longevity for deliverability. The two controls oppose one another, which is why the ensemble appears to flatten above $f_{\text{void}} = 0.75$ in Figure 7a: those realisations coarsen as they open. The void-fraction response itself does not weaken, and holding room width at 30 m TPL still increases from 1025 to 1220 d as f_{void} rises from 0.781 to 0.863 (G1405B to G1407B). Bulk void fraction is therefore the first-order control on thermal longevity within Scenario A and the pillar-and-void length-scale a second-order one.

Scenario B introduces a partial coal barrier across the inter-well flow path, restricting the direct connectivity present in the baseline model (Figure 7b). Each barrier configuration increases the inter-well pressure differential above the baseline value ($\Delta p = 0.45$ bar; Section 3.1), correspondingly reducing PI. Flow is most constricted in the longest-barrier case (G1442B), where Δp rises to 0.86 bar and PI roughly halves to $1940 \text{ m}^3 \text{ d}^{-1} \text{ bar}^{-1}$. G1444B covers more area than G1443B yet maintains a similar pressure differential ($\Delta p \approx 0.63$ bar) and productivity index ($\text{PI} \approx 2620 \text{ m}^3 \text{ d}^{-1} \text{ bar}^{-1}$), indicating that increasing barrier width at a constant length yields minimal impact. As shown by the plateau in the barrier-width curve (Figure 7b), once a barrier exceeds a critical width, adding material behind the barrier face yields no further hydraulic resistance. Inter-well connectivity is thus governed by how effectively a barrier blocks the direct path between wells, rather than total coal barrier volume. In contrast to Scenario A, flow barriers improve thermal lifetime (TPL ≈ 1710 d to 2060 d versus 1225 d at baseline): the enforced flow detour around the barrier edges extends the sweep path and delays thermal breakthrough. Without a barrier, the cooling front migrates directly along the inter-well axis; an extended barrier retains cold water on the injection side, forcing lateral thermal spreading prior to producer breakthrough (Figure 8c, d).

Scenario C models hold static void volume approximately constant ($v_v \approx 402 \times 10^3 \text{ m}^3$ to $418 \times 10^3 \text{ m}^3$) while varying the proportion of void volume hydraulically connected to the doublet. Across the three cases shown in Figure 7c, productivity index declines by only ≈ 13 % ($939 \text{ m}^3 \text{ d}^{-1} \text{ bar}^{-1}$ to $816 \text{ m}^3 \text{ d}^{-1} \text{ bar}^{-1}$), whereas thermal production lifetime drops from 917 d (connected, G1463B) to 532 d (tortuous, G1465B) and ultimately 46 d (bypassed, G1467B). With total storage capacity fixed by design, this twenty-fold reduction in thermal lifetime is driven entirely by mine connectivity. As a larger share of the void network becomes tortuous or completely bypassed, the volume swept by circulating fluid shrinks, accelerating cold-front arrival at the producer despite unchanged total heat-in-place (Figure 8e, f). This highlights an insight that volumetric storage-based estimates alone might overlook: thermal longevity is

governed by the hydraulically connected, swept void volume rather than gross static void volume. Furthermore, because TPL collapses by $\approx 95\%$ compared to a marginal $\approx 13\%$ decline in PI, Scenario C reveals a subtle diagnostic risk: standard short-term hydraulic pumping tests, which measure productivity, may provide virtually no indication of thermal bypassing in mixed-extraction type workings.

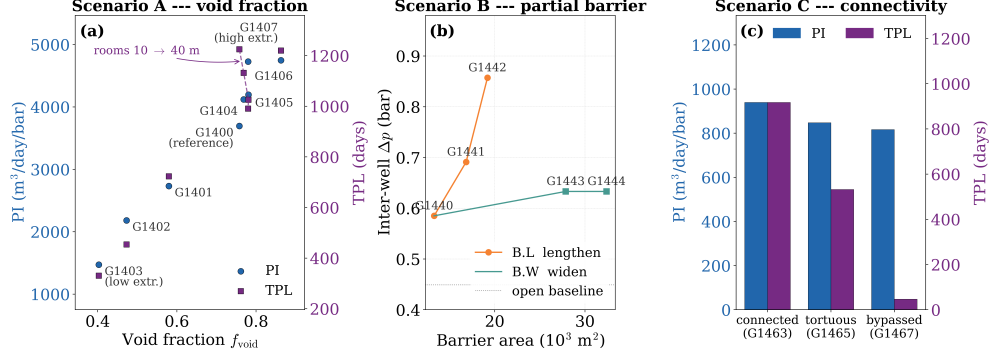


Figure 7: Thermal-Hydraulic performance of the mine geometry realisations. (a) Scenario A varies the bulk void fraction. The dashed line links four realisations whose rooms and pillars coarsen together from 10 m (G1400B) through 20 m (G1404B) and 30 m (G1405B) to 40 m (G1406B); (b) Scenario B introduces a partial flow barrier across the doublet, lengthened at fixed width (B.L, $w = 30$ m) or widened at fixed length (B.W, $L = 466$ m), with the dotted line marking the open, no-barrier baseline at $\Delta p = 0.45$ bar; and (c) Scenario C reduces mine connectivity while keeping the static void volume across the galleries fixed at $v_v \approx 402\text{--}418 \times 10^3 \text{ m}^3$.

3.3 Material-Property Controls on Performance

Backfill volume (BV), backfill properties (BP) and void properties (VP) are evaluated across six representative mine-geometry models under both host-rock scenarios (Figure 9). The wider host-rock contrast across all sixteen geometries is taken up in Section 3.4.

Increasing backfill volume reduces both deliverability and thermal lifetime in every geometry tested (Figure 9a,d). Backfill replaces the highly permeable voids down-dip of the structure, with a relatively lower-permeability matrix, raising the inter-well pressure differential and shrinking the connected void volume swept during circulation. The shape of the decline depends on internal mine architecture.

In the well-connected Scenario A model (G1400B), performance declines smoothly and monotonically. The gallery mesh offers many alternative routes between the wells, so filling one void diverts circulation into its neighbours rather than severing the path. Δp rises only from 0.45 to 0.56 bar, a corresponding PI drop of 19% from 3693 to 2983 $\text{m}^3 \text{d}^{-1} \text{bar}^{-1}$. Thermal lifetime is far more sensitive, falling 61% from 1225 to 473 d: the detour preserves hydraulic access to the working but not the stored heat displaced by backfill.

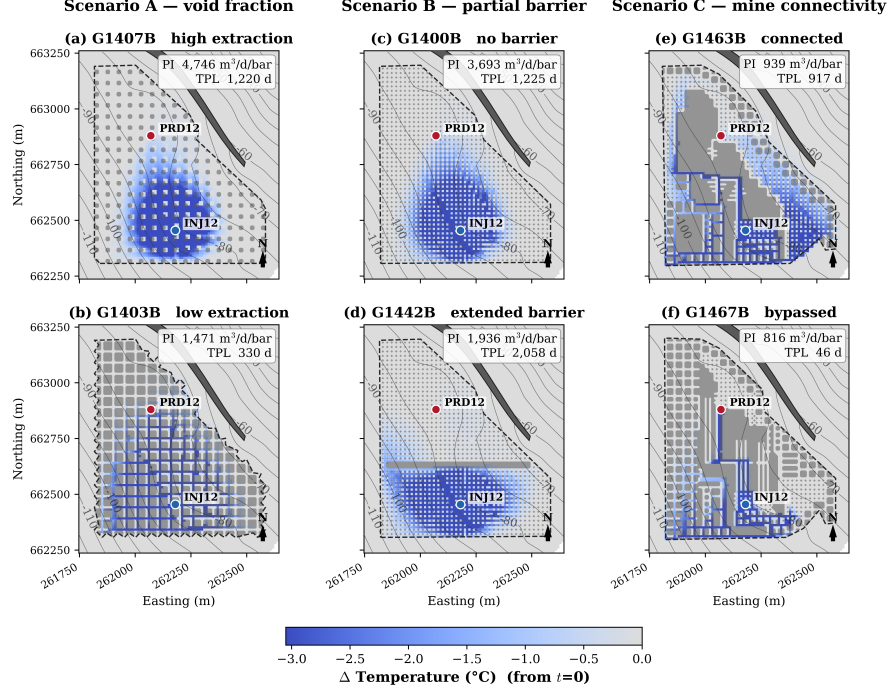


Figure 8: Temperature change in the worked seam after 180 d. Panels show ΔT from $t = 0$ at reference conditions (S1, BV1_BP3_VP3). Grey is solid coal, so the coloured plume shows only the open workings. The dashed black line is the worked mine boundary, thin grey lines are depth contours in (m OD), also showing the Blythswood fault.

Scenario B workings degrade in steps. In G1440B, PI holds to 7.5 % backfill (BV2) and then falls 39 %, from $2640 \text{ m}^3 \text{ d}^{-1} \text{ bar}^{-1}$ at 22.5 % (BV4), as backfill seals the primary conduits within the borehole drainage area. Thermal lifetime steps with it, from 1570 to 1013 d. As the open galleries between the backfill and the partial barrier fill, the pressure gradient driving circulation is diverted out of the galleries and vertically into the confining layers (Figure 10). The step in Figure 9a marks the backfill volume at which fill and barrier together sever the last open route between the wells. The response is sharper in the longest-barrier case (G1442B), where the first 7.5 % increment (BV2) constricts flow enough to drop PI from 1936 to $931 \text{ m}^3 \text{ d}^{-1} \text{ bar}^{-1}$ and TPL from 2058 to 1208 d. Unlike G1440B, which has the shortest barrier and continues to decline, further backfill barely affects G1442B.

Heterogeneous Scenario C models step in the same way, but the threshold moves. These three realisations hold the same static void volume and differ only in how it is connected, so the backfill volume at which performance breaks down is set by connectivity alone: G1463B loses 31 % of its PI at 15 % backfill (BV3, 914 to $633 \text{ m}^3 \text{ d}^{-1} \text{ bar}^{-1}$), whereas the tortuous G1465B and bypassed G1467B hold until 22.5 % (BV4). G1467B is short-circuited from the outset, so its lifetime sits an order of magnitude below every other realisation at every fill level (22 d to 46 d), yet its

deliverability still falls 29 % across the sweep. Backfill continues to restrict circulation even where geometry has already fixed the thermal outcome.

Co-varying backfill porosity and permeability under a fixed 15 % backfill volume (Table A1; Figure 9b,e) changes almost nothing. PI varies by at most 2.1 % and TPL by at most 6.4 % in every realisation, and by at most 1.3 % and 6.2 % under S2, despite a near five-fold range in permeability (460 to 2175 mD). The constraint is geometric. Backfill sits away from the direct inter-well axis and, even at its most permeable, remains over two orders of magnitude below the open voids that carry the advective flow, so it conducts a negligible share of the circulating fluid whatever its matrix state. Backfill material properties are thus a second-order control.

Void properties (porosity and permeability scaled simultaneously, VP1 to VP5) exert a first-order control on deliverability but only a second-order control on thermal lifetime, with both responses dictated by the hydraulic resistance and volumetric heat capacity assigned to the gallery network (Table A3). Permeability governs internal hydraulic resistance; the most permeable voids sustain the lowest inter-well pressure differentials, giving a productivity index (PI) higher by a factor of 6.1 to 7.1 than the tightest in every realisation (Figure 9c). However, absolute deliverability remains strictly constrained by spatial mine architecture (Scenario A > Scenario B > Scenario C). Furthermore, the vertical separation between the sealed (S1) and leaky (S2) curves, compressed by the logarithmic axis, shows that host-rock permeability also raises deliverability: at the 15 % reference backfill volume it adds 19 % to 77 % at VP1 in five of the six realisations, decaying to 1 % to 18 % by VP5.

Under sealed host-rock conditions (S1), thermal production lifetime (TPL) is modestly and monotonically lower in more permeable voids, by 3 % to 20 % (Figure 9f). Circulation is strictly confined within the gallery network under a constant flow rate, so more permeable voids lessen conductive heat extraction from surrounding strata. This TPL reduction is minimal in open, well-connected meshes (3 % in G1400B) but reaches 20 % in restricted circuits (G1467B). Counterintuitively, increasing void porosity fails to delay thermal breakthrough. Mine voids are assigned the volumetric heat capacity of water (Table A3), so increasing pore volume by one-third displaces an equal volume of matrix carrying that same capacity, which would otherwise have provided thermal retardation. Consequently, thermal breakthrough shortens by up to 16 % across the sweep, showing that void porosity expansion cannot counteract advective short-circuiting in sealed systems.

The response under leaky host-rock conditions (S2) reveals a strong non-linear coupling between void properties and matrix thermal recharge. Matrix thermal storage is recruited whenever the void network is hydraulically restricted, a behaviour mirrored in the backfill sensitivity sweep, where workings losing over a third of their deliverability (G1440B, G1442B and G1463B) show S2 lifetime gains growing by 17 % to 44 %. That step falls at the same backfill level under both host rocks, but S2 makes it shallower, easing the PI drop from 31 to 21 % in G1463B and from 21 to 10 % in G1467B. In the void property sweep, at low void permeability (VP1), elevated internal hydraulic resistance forces fluid into surrounding strata, mobilising the vast thermal mass of the host rock. This interaction extends TPL over S1 baselines by a factor of ≈ 1.2 in open meshes (Scenario A), 1.5–2.1 in partial-barrier geometries (Scenario B),

and 3.4–12.1 in restricted geometries (Scenario C), extending the TPL of the bypassed G1467B system from 40 to 488 d. As void permeability increases (VP5), the mine network transitions into a path of minimal hydraulic resistance, drawing fluid back into the galleries and bypassing matrix storage. By VP5, the S2 lifetime enhancement collapses to a factor of just 1.0–1.6 across all realisations. Consequently, while the TPL difference between the tightest and most permeable voids is only 3 % to 20 % under S1, it reaches 18 % to 90 % under S2. Void permeability and host-rock permeability are therefore strongly interdependent controls, demonstrating that the thermal buffering benefit of a leaky confining sequence cannot be evaluated independently of intrinsic void permeability.

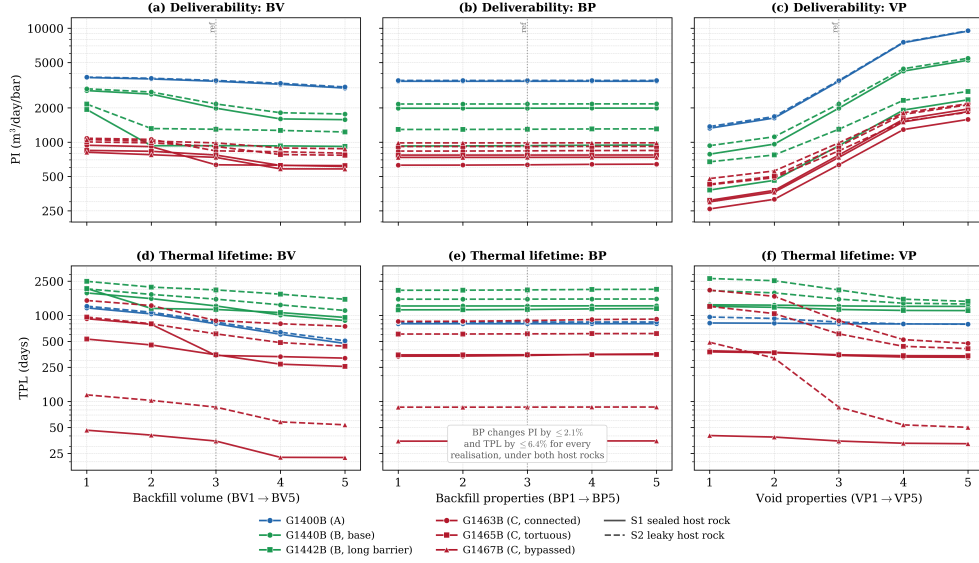


Figure 9: Material-property controls on coupled thermal-hydraulic performance across the six representative geometries. In each column one parameter is varied over five levels about the shared BV3_BP3_VP3 reference (level 3; Table A1), under sealed (S1, solid) and leaky (S2, dashed) host rock.

3.4 Host-Rock Controls on Performance

The two host-rock scenarios, S1 (low-porosity, low-permeability sealed confining strata) and S2 (high-porosity, high-permeability leaky confining strata), differ by roughly three orders of magnitude in overburden and underburden permeability while sharing identical mine gallery geometries. Evaluated across all 16 geometries at the zero-backfill baseline BV1_BP3_VP3 (Figure 11), S2 increases both deliverability and thermal lifetime, with the magnitude of those gains varying systematically with the mine’s internal connectivity.

For highly connected workings (Scenario A), switching from S1 to S2 yields only a modest PI gain of $\approx 2\%$ (Figure 11), because permeable host rock simply provides an

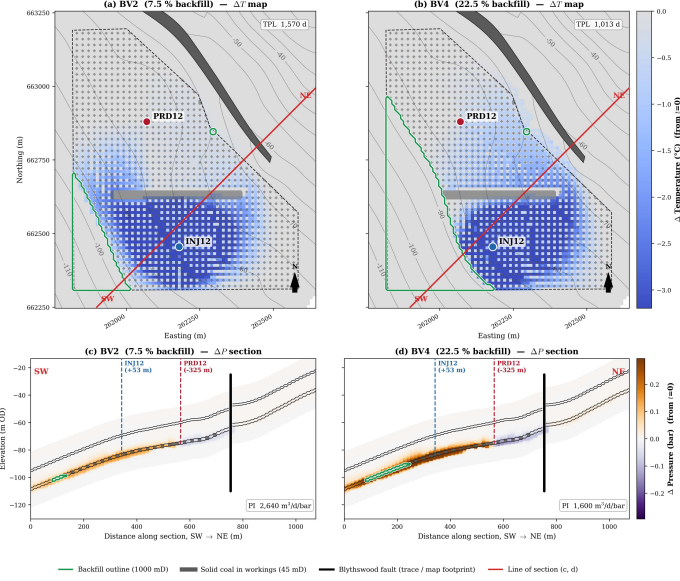


Figure 10: Backfill volume in the partial barrier Scenario B working G1440B at 180 d. (a, b) Temperature change (ΔT from $t = 0$) in the seam at 7.5 % (BV2) and 22.5 % (BV4) backfill. (c, d) Pressure change (ΔP) along the SW-NE line drawn in red on the maps. Thin grey lines on the maps are seam depth contours (m OD). INJ12 and PRD12 are projected onto the line from the offsets shown. Backfill presence pushes the cooled water out of the down-dip galleries and increases the effective pressure gradient in the mine gallery.

alternative vertical path that duplicates already efficient gallery flow. Where connectivity is reduced (by partial coal barriers in Scenario B, or by tortuous and bypassed galleries in Scenario C), that same vertical path delivers a materially larger gain. PI increases by $\approx 6\%$ in partial-barrier cases and by $\approx 21\%$ across Scenario C, reaching $+29\%$ in the most extreme bypassed geometry (G1467B). Fluid flow through overburden and underburden strata thus acts as a hydraulic bypass whose relative benefit scales inversely with internal mine connectivity.

Thermal lifetime increases under S2 conditions for every geometry (Figure 11), rising by $\approx 7\%$ in Scenario A, $\approx 15\%$ in Scenario B, and $\approx 100\%$ in Scenario C. In the bypassed case G1467B, longevity more than doubles, from 46 to 120 d (a $+158\%$ improvement). Hydraulic bypass registers immediately in the pressure field, whereas thermal buffering develops gradually as fluid resides within the host rock. Flow into the more permeable S2 strata engages a much larger thermal mass than the mine void alone, diffusing and delaying the cold front. Under constant-rate circulation this exchange continues even as the inter-well pressure difference falls: in G1467B, S2 cools 29% more confining rock than S1 despite operating at a 22% lower Δp . Host-rock permeability therefore remains a second-order control on hydraulic deliverability at this zero-backfill baseline, even in the most restricted geometry, whereas its role in thermal longevity is conditional, rising from second-order in well-connected workings to first-order only where the void network is poorly connected. The size of both gains is itself set by void permeability (Section 3.3).

These dual mechanisms are most clearly isolated in the bypassed Scenario C end-member (G1467B), where the host-rock influence is strongest (Figure 11); the same behaviour appears throughout the ensemble but with reduced magnitude. Under S2 conditions, the leaky confining sequence damps the early-time bottom-hole pressure transients at both wells (Figure 12a) and delays the producer temperature decline (Figure 12b). Although both scenarios remain short-lived in absolute terms (46 d under S1 and 120 d under S2), the contrast highlights the underlying mechanism rather than a viable operating case. Cross-sectional profiles reveal the source of the performance change (Figure 13): thermal drawdown under S1 is confined to the worked coal seams, whereas under S2 it extends substantially into the overburden and underburden. The circulating fluid is thus distributed through a much larger rock volume, rather than being limited to direct inter-well voids, providing a clear spatial explanation for the observed TPL gains.

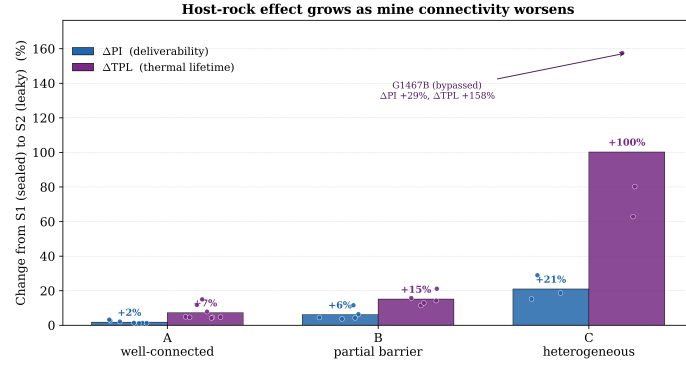


Figure 11: Host-rock controls on deliverability and thermal longevity. Change from sealed (S1) to leaky (S2) confining layers, for all sixteen geometries at the zero-backfill baseline (BV1_BP3_VP3); bars are the scenario mean, dots the individual geometries.

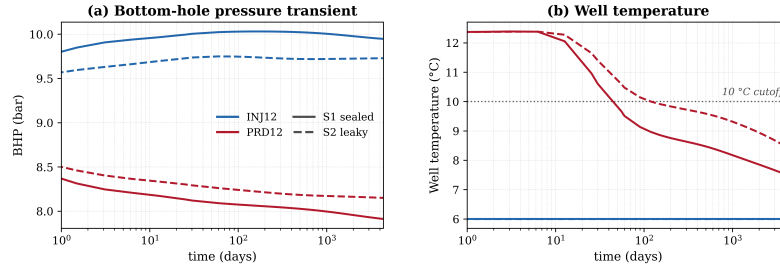


Figure 12: 12-year well response for G1467B, comparing sealed (S1) and leaky (S2) confining layers.

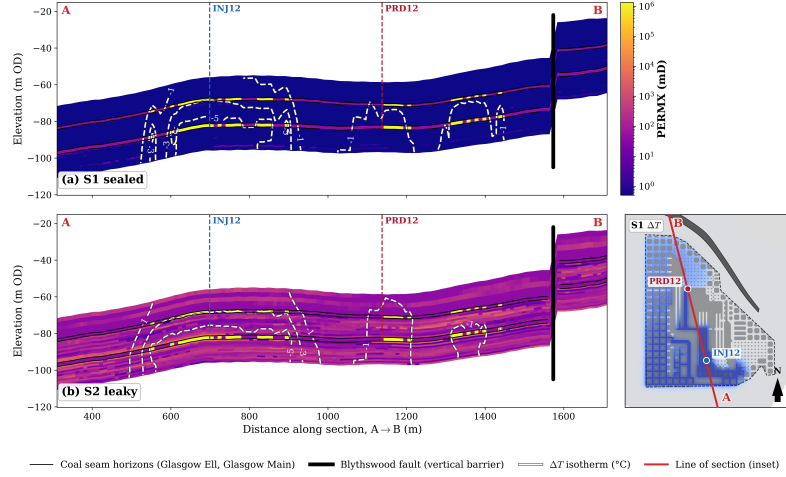


Figure 13: Thermal response for G1467B along cross-section A → B. Panels show permeability distribution in (a) sealed S1 and (b) leaky S2 confining layers. Isotherms are at -5 , -3 and -1 °C extracted after 12 years. The inset locates the cross section on the ΔT map of the working. Under S1 the cooling into the host rock is conduction-limited; under S2 it spreads more into the overburden where the cooled volume roughly doubles, delaying thermal breakthrough as shown in Figure 12b.

4 Discussion

4.1 Factors Controlling Thermal-Hydraulic Performance

Deliverability and thermal longevity are governed by different geometric controls, and the three scenarios (Section 3.2) show that the relationship between them is not fixed. Raising the void fraction in Scenario A widens the flow paths and enlarges the swept volume together, so both metrics rise. That agreement does not hold even within Scenario A: at constant void fraction, coarsening the pillar-and-void length-scale raises PI by 28 % while shortening lifetime by 19 %. Scenario B inverts the relationship outright, as partial barriers force detours that reduce deliverability while extending thermal life, and performance follows how effectively a barrier blocks the direct inter-well pathway rather than its bulk volume. Scenario C provides the decisive contrast: holding storage capacity constant while varying network connectivity collapses thermal lifetime roughly twenty-fold for a productivity loss of about 13 %.

Consequently, thermal longevity is governed by the hydraulically connected, swept void volume rather than gross heat-in-place. Gross storage capacity is a necessary but insufficient predictor of usable thermal resources within this context. This distinction refines static capacity representations used in earlier mine-water energy studies (Perez Silva et al. 2022; Guo et al. 2023) and underscores the necessity of explicitly resolving complex void networks detailed in previous studies (Adams and Younger 2001; Renz et al. 2009; Hamm and Bazargan Sabet 2010; Loredó et al. 2016). By holding static void volume constant, our ensemble approach isolates this connectivity effect, showing that uncontacted voids contribute nothing to energy extraction. Even in the well-connected baseline, the circulating water contacts only a fraction of

the heat within the modelled domain, giving a recovery factor of $\eta \approx 0.08$ above the economic cutoff (Section 3.1).

This control is not specific to mine geometry. In fluvial clastic geothermal reservoirs, doublet lifetime falls sharply once facies connectivity degrades, and homogenising heterogeneous reservoir bodies overestimates it (Crooijmans et al. 2016). That same homogenisation also regularises the cold-plume geometry, and replacing 3D heterogeneous models with upscaled 2D equivalents shifts the stochastic response of a Monte Carlo ensemble rather than merely its spread (Wang et al. 2023). Where heterogeneity is discrete rather than continuous, as in fractured high-enthalpy reservoirs, thermal breakthrough follows the connected fracture network, and coarsening that network alters the predicted production temperature even where bulk properties are preserved (Wang et al. 2021). A mine differs in that its high-permeability network is engineered and partially mapped, but the consequence for performance is the same: what governs the outcome is the portion of the network that the circulating water reaches. Since no single geological description can be selected a priori, recent work on fluvial geothermal systems carries multiple geological scenarios through data assimilation and falsifies those inconsistent with observed data (Song et al. 2026), an approach analogous to the ensemble of mine-architecture scenarios used here.

Backfill acts as a spatial modifier of network connectivity rather than a standalone, independent parameter (Section 3.3). Although variations in backfill material properties are known to reroute subsurface flow (Renz et al. 2009; Yang 2016), their operational impact depends critically on spatial placement relative to the principal inter-well flow path rather than their bulk volume or matrix properties alone. When emplaced in down-dip workings off the direct circulation axis, backfill is largely bypassed by advective fluid flux, rendering its internal permeability variations negligible. Conversely, if backfill directly intersects active inter-well flow paths, it becomes a bottleneck with no route around it, analogous to the partial coal barriers in Scenario B, elevating its petrophysical properties to a first-order control. Consequently, backfill material properties modulate doublet performance only when occupying active, hydraulically connected circulation conduits.

The relative influence of geological properties versus operational parameters on system deliverability and thermal stability remains a point of debate in the literature. Perez Silva et al. (2022) conclude that conductive heat transport in flooded coal mines is strongly governed by local petrology and lithological distributions. In contrast, Mouli-Castillo et al. (2024) propose a different hierarchy of influence: while acknowledging that rock thermal conductivity outweighs specific heat capacity, they argue that operational flow rate variations exert a far more dominant effect on thermal performance. Todd et al. (2024) reinforce this operational focus, asserting that managing injection temperature profiles is the primary driver for efficient scheme operation, relegating mine geometry and geological properties to secondary importance. This creates a clear dichotomy in the literature between studies prioritising detailed lithological characterisation and those advocating active operational control as the primary determinant of system success.

Our results address the subsurface side of this debate (Section 3.4). Operational controls were held constant throughout (Section 4.3), so they cannot be ranked against

geological ones here. Across homogeneous, stratified and heterogeneous representations of the same low-enthalpy system, reservoir depth and discharge rate rank as the dominant controls on performance, with the geological description modulating rather than displacing them (Chen et al. 2025). What the ensemble does show is that the geological control is itself conditional. Permeable overburden and underburden strata act on both metrics, and both effects strengthen as connectivity worsens, but they differ by an order of magnitude: thermal recharge occurs via slow conductive–convective transport and gradual fluid exchange with adjacent strata, which buffers the cold front where the void network is poorly connected (100% in Scenario C) but adds little where the galleries already sweep efficiently (7% in Scenario A), while the corresponding gain in deliverability runs only from 2 to 21% across the same scenarios. In a heterogeneous 3D domain, the relationship between deliverability and thermal longevity is inherently non-unique: the performance metrics correlate positively along Scenario A’s void-fraction axis, exhibit an inverse trade-off in Scenario B, and decouple almost entirely in Scenario C. The full ensemble performance map (Figure 14) confirms that no single geometric or material parameter simultaneously maximises both metrics, leaving the high-deliverability, long-life quadrant unpopulated.

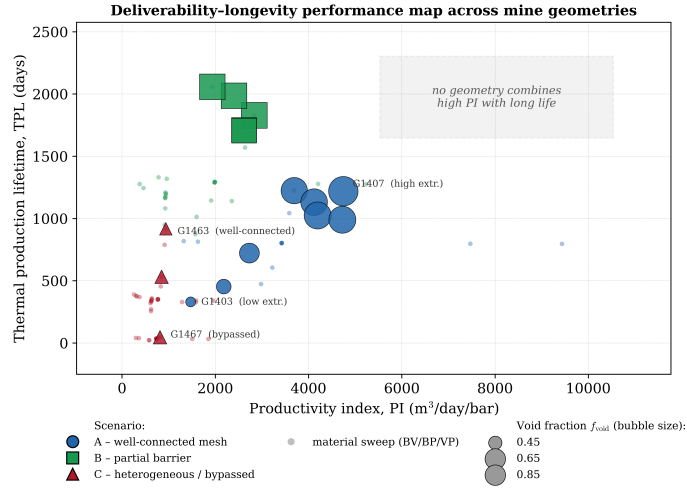


Figure 14: Deliverability–longevity performance map across the sixteen geometry baselines (S1_BV1.BP3.VP3). Thermal production lifetime (TPL) is plotted against productivity index (PI). Bubble size scales with void fraction; colour and symbol denote scenario. Faint clouds are the material-property sweeps (BV, BP, VP) run for the six representative geometries, 13 runs each.

4.2 Implications for Site Characterisation and Scheme Design

Injector-to-producer connectivity dictates both hydraulic deliverability and thermal longevity (Sections 3.2 and 3.3). Early site characterisation should prioritise delineating mined boundaries and localised structural features along the direct inter-well

circulation path. Unworked coal barriers, stoppings, and unmapped void networks redirect fluid pathways. Detailed legacy plans thus offer far greater predictive utility than gross extracted tonnage or static void volumetric reports. Host-rock heterogeneity cannot be fully quantified a priori, so modelling distinct end-member scenarios clarifies technical risks for engineering design teams and supports phased capital commitment as site uncertainty resolves. Prior to full field development, baseline pressure-transient testing, evaluating early buildup and drawdown (Section 2.7.1), can directly quantify near-wellbore connectivity, while quasi-steady-state stabilisation testing prevents overestimating usable thermal capacity.

Simulation confidence depends on the fidelity of archived data. Legacy coalfield abandonment plans frequently rely on qualitative records grounded in miners’ tacit experience, and many vintage plans fail to distinguish intact coal barriers from backfill or galleries abandoned under controlled collapse (goaf). The very structural features that set subsurface connectivity remain ambiguous even where plans survive, strongly favouring scenario-based feasibility screening over deterministic single-value estimates at poorly characterised sites. Well placement is therefore the principal pre-drill lever on connectivity: siting should aim to maximise connected flow pathways, leveraging internal barriers as strategic assets for thermal longevity rather than viewing them merely as flow obstructions.

Scheme design should directly align with target operational demand profiles. High-demand, head-limited systems benefit from highly connected gallery networks with elevated productivity indices (PI). Conversely, baseload, duration-limited schemes can accept lower deliverability to exploit the extended thermal sweep of the partial-barrier workings (Scenario B). Operating parameters trade flow rate against dynamic head without altering primary subsurface controls. Host-rock properties offer an additional design lever (Section 3.4): permeable overburden extends operational lifespan in continuous circulation schemes, whereas low-permeability host rocks better isolate heat for seasonal Mine Thermal Energy Storage (MTES), an operational regime requiring cyclic injection–recovery simulations to fully quantify.

4.3 Limitations and Assumptions

Our numerical simulations omit certain coupled physical processes that bound system performance in predictable ways. First, fluid flow is modelled as single-phase liquid, which holds for shallow, low-temperature systems but does not account for boiling and dissolved gas exsolution (e.g., methane) below the bubble-point pressure. Second, confining layers are assumed mechanically rigid; pore volume responds linearly with uniform rock compressibility across lithologies (Section 2.4), omitting stress-path dependencies, coupled compaction–permeability feedbacks, and inelastic hysteresis. Under the rate-controlled conditions imposed here, compressibility governs the early-time pressure transient rather than the late-time inter-well differential from which Δp and PI are evaluated (Equation 1), so the comparisons drawn between geometries are not expected to be sensitive to it. Fully coupled hydro-mechanical responses (including stress-dependent permeability evolution, backfill compaction, and surface ground movement) are therefore not represented (Section 5).

Subsurface facies and petrophysical properties are modelled as single spatial realisations for scenarios S1 and S2. Cyclical fluvial coal sequences typically feature complex facies variations and anisotropic fracture networks that redirect inter-well flow, making local host-rock effects more spatially variable than a single S1/S2 contrast implies. Model parameterisation relies on the exploratory borehole GGC01, located away from the primary workings (Section 2.1), so lateral continuity remains weakly constrained. The S1 and S2 end-member scenarios (Section 2.5) thus represent a pragmatic engineering approach to bound spatial uncertainty rather than a substitute for full site characterisation.

Sensitivity analysis was conducted one parameter at a time (OAT) relative to a reference baseline. While this isolates primary controlling mechanisms, it does not capture non-linear factor interactions (Section 4.1); results must therefore be interpreted as contingent on the specific model geometries and on the petrophysical property ranges sampled (Table A1) rather than as universal constants. The direction and mechanism of each response are expected to transfer to other flooded workings, whereas the magnitudes quoted throughout are properties of this ensemble: a working with a different spatial porosity-permeability distribution would be expected to reproduce the trends, not the percentages. Resolving complex two-factor interactions (e.g., simultaneous high backfill volume and elevated void permeability) requires targeted multi-variable simulations. Furthermore, operational and thermal boundary conditions were held constant, precluding cross-factor sensitivity rankings across varying operating regimes.

Each performance metric is defined against a predefined threshold rather than a physical transition. For example, thermal breakthrough and lifetime metrics shift in absolute terms under alternative cutoff choices, although the relative performance ranking among scenarios is preserved: recomputing thermal lifetime for cutoffs between 9 and 11 °C leaves the scenario ordering unchanged, and individual geometries transpose only where their lifetimes differ by less than 7%. Similarly, the recovery factor (Equation 4) references both of its terms to the 10 °C abandonment temperature, and therefore depends directly on that threshold and on the 3D domain volumetric bounds (Section 2.5); it thus serves as a relative comparative index rather than an absolute commercial yield.

Finally, our simulations are idealised as a single doublet operating under constant-rate, loss-free, balanced circulation, and performance is assessed under a direct-use framing in which produced mine water supplies heat directly to demand without heat-pump upgrading. The cutoff temperature therefore acts as a firm operational constraint, and surface parasitic losses such as pumping power are excluded; a scheme that upgraded the produced water through a heat pump would remain viable below that cutoff. Commercial multi-well schemes featuring variable demand profiles, wellbore skin losses, or multi-seam cycling may diverge in absolute performance, though the geometric and material controls identified here remain the primary ones. As regional mine-water abstraction expands, inter-well interference between adjacent schemes may cause thermal short-circuiting, alter local host-rock heat content, or induce rapid draw-down in offset wells. Managing these regional hydraulic and thermal interaction risks through field-wide monitoring and coordinated operation must therefore be treated as a design priority for multi-operator mine-water energy schemes.

5 Conclusion

Using an ensemble of conceptual mine geometry and geological realisations, we characterised the coupled thermal-hydraulic response of a flooded coal mine operated as an open-loop doublet with cold-water reinjection. Specifically, we evaluated whether deliverability and thermal longevity share identical subsurface controls, and whether operational thermal lifetime reflects total in-place heat storage or the hydraulically connected void volume swept by circulating fluid. Our findings demonstrate that deliverability and longevity are governed by different mechanisms: deliverability depends on the open, connected cross-sectional flow area between wells, whereas thermal longevity is dictated by the swept void volume and surrounding host-rock thermal recharge. High intrinsic connectivity enhances deliverability but accelerates thermal breakthrough, so no single mine architecture simultaneously maximises both metrics, leaving the high-deliverability, long-life quadrant unpopulated (Section 4.1).

Holding static void volume constant while varying network connectivity collapses thermal production lifetime roughly twenty-fold in sealed-host systems, whereas the productivity index falls by only $\approx 13\%$ (Section 3.2). Thermal longevity is thus governed by connected, swept void volume rather than static heat-in-place, of which only a small fraction ($\eta \approx 0.08$) above the economic cutoff is recovered before thermal short-circuiting occurs (Section 3.1). Mine geometry acts as the primary, first-order design control that bounds achievable system performance. Regarding void properties, more permeable voids scale deliverability without altering the geometric hierarchy, yet carry a thermal lifetime shorter by 3% to 20% under a sealed host rock across all evaluated realisations; the added pore volume brings no storage gain, while the higher permeability confines circulation strictly to gallery conduits. Backfill material properties exert no measurable influence once backfill lies off the inter-well circulation path; thus, spatial placement, rather than material composition, dictates backfill impact (Section 3.3). Host-rock permeability influences both metrics, with both effects amplifying as void connectivity degrades. However, these impacts differ by an order of magnitude: a leaky (S2) confining sequence improves deliverability only modestly, whereas its influence on thermal longevity is conditional—remaining second-order in well-connected workings, but becoming first-order in disconnected networks, or where doublet target placement causes thermal bypass. The two controls are thus strongly coupled, with the leaky sequence contributing most where gallery voids are tight (Section 3.4).

When re-engineering abandoned coal mines for open-loop thermal energy applications, site characterisation must prioritise mapping connectivity features along the direct inter-well circulation path, such as flow barriers, stoppings, and standing pillars, rather than relying solely on extraction ratios or gross mine footprint. Energy resources should be assessed on the heat that can actually be recovered rather than on gross heat-in-place capacity. Where historical abandonment records are uncertain, the scenario spread itself provides a robust probabilistic envelope, favouring scenario-based screening and phased capital commitment alongside baseline pressure-transient testing to quantify near-well connectivity. Furthermore, scheme design must align with operational objectives: doublets in conventional coal mine systems, without heat injection, perform best when mine voids are paired with permeable host rock layers, which provide essential thermal recharge to extend system lifetime (Section 4.2).

Future extensions of this work target seasonal storage-mode operations (Mine Thermal Energy Storage, MTES) by imposing cyclic injection–recovery regimes to evaluate how host-rock heterogeneity governs transient thermal-hydraulic performance. Furthermore, fully coupling fluid flow with rock deformation will define safe operational envelopes by evaluating how cyclic pressure variations–driven by the hydraulic loading and unloading of mine gallery networks–influence long-term ground stability; subsidence, or uplift. Together, these advances will translate thermal-hydraulic characterisations into the coupled, predictive operational forecasts required for sustainable, commercial mine-energy developments.

Acknowledgements. We are grateful to the British Geological Survey (BGS) for open access to the multi-scale, multi-disciplinary UKGEOS datasets that made this study possible. Special thanks go to Delft University of Technology (TU Delft) for hosting the corresponding author during his research visit and providing access to its facilities. The authors also thank Andrés González-Quirós (BGS) for valuable input during the early stages of this work, and Dan Arnold (Heriot-Watt), Ilshat Saifullin (TU Delft) and Femi Onita (Shell) for helpful discussions and comments that improved the subsurface workflow.

Declarations

Funding. The research leading to these results received funding from the UK Engineering and Physical Sciences Research Council (EPSRC) through a doctoral studentship at Heriot-Watt University. Heriot-Watt University also funded a research visit to the Department of Geoscience and Engineering at TU Delft.

Conflict of interest. The authors have no conflict of interest to declare that are relevant to the content of this article.

Ethics approval and consent to participate. Not applicable.

Consent for publication. Not applicable.

Data availability. GGC01 borehole data underpinning the geological model of the Glasgow UK Geoenery Observatories (UKGEOS) are openly available in (Monaghan et al. 2021) based upon data provided by the British Geological Survey © UKRI. All rights reserved. The post-drill coal mine model for the Glasgow site and the hydro-geological test pumping data are available from the NERC EDS National Geoscience Data Centre (Kearsey and Burkin 2021b; Shorter et al. 2021). The 3D grids and simulation outputs generated in this study are large and available from the corresponding author on reasonable request.

Code availability. The simulations were run with the open-DARTS multiphysics simulator (Voskov et al. 2024), which is open source and available at <https://gitlab.com/open-darts/open-darts>.

Author contributions. **A.A.:** conceptualisation, methodology, investigation (open-DARTS simulations), formal analysis, visualisation, writing-original draft. **E.M.C.:** conceptualisation, methodology, validation, funding acquisition, supervision,

writing-review and editing. **V.D.:** conceptualisation, methodology, validation, computing resources, supervision, writing-review and editing. **D.V.:** software, validation, writing-review and editing. All authors read and approved the final manuscript.

Abbreviations

ATES	Aquifer thermal energy storage
BGS	British Geological Survey
BHP	Bottom-hole pressure
BP	Backfill properties (porosity–permeability)
BV	Backfill volume
DARTS	Delft Advanced Research Terra Simulator
DGSA	Distance-based generalised sensitivity analysis
HF8 / HF9 / HF10	Hydraulic facies: coal / backfill / mine void
INJ	Injector well (e.g. INJ12)
MG	Mine geometry
MSCL	Multi-sensor core logger
MTES	Mine thermal energy storage
OAT	One-at-a-time (sensitivity design)
OBL	Operator-based linearisation
OD	Ordnance Datum (elevation)
PI	Productivity index (or Deliverability)
PRD	Producer well (e.g. PRD12)
SE	South-east
TBT	Thermal breakthrough time
THM	Thermal-hydraulic-mechanical (coupled)
TPL	Thermal production lifetime
UKGEOS	UK Geoenergy Observatory
VP	Void properties (porosity–permeability)

Appendix A Model parameter values

Table A1: Group I parameter levels for the one-at-a-time sweeps. BV is the backfill volume as a percentage of worked-region bulk volume; BP and VP are the porosity ϕ and permeability k of the backfill (HF9) and mine void (HF10), swept together as a coherent physical state.

Level	BV	BP (backfill)		VP (mine void)	
	(%)	ϕ	k (mD)	ϕ	k (mD)
1 (very low)	0	0.1596	460	0.7452	542 304
2 (low)	7.5	0.1855	546	0.7878	663 336
3 (mid, ref)	15	0.3000	1000	0.9184	1 350 000
4 (high)	22.5	0.4190	1832	0.9842	2 747 800
5 (very high)	30	0.4512	2175	0.9916	3 361 060

Table A2: Six mine-geometry realisations used for the Group I material-property sweeps. The sweeps are those defined in Table A1, and the realisations are categorised by scenario. Each is run through the thirteen-combination one-at-a-time (OAT) design (centred on BV3_BP3_VP3) under both host-rock scenarios (S1 sealed, S2 leaky). With the ten remaining geometries evaluated once at zero backfill (BV1) under each scenario, the ensemble totals $[(6 \times 13) + (10 \times 1)] \times 2 = 176$ coupled simulations.

Scenario	Connectivity role	Full model name (OAT centre, 15 % BV)
A	well-connected room-and-pillar	G1400B_S1_BV3_BP3_VP3
B	short partial barrier	G1440B_S1_BV3_BP3_VP3
B	extended partial barrier	G1442B_S1_BV3_BP3_VP3
C	connected (fixed storage)	G1463B_S1_BV3_BP3_VP3
C	tortuous	G1465B_S1_BV3_BP3_VP3
C	bypassed	G1467B_S1_BV3_BP3_VP3

Table A3: Hydraulic facies properties. (ϕ , k) are uniform for HF8–HF10 and P5–P95 for HF2–HF7, and are the only properties differing between S1 and S2. ($C_{V,s}$, λ) are matrix bounds, as used in Equation 4; the water-filled void HF10 takes water’s values.

Facies	S1 (sealed)		S2 (leaky)		HEATCR ($C_{V,s}$)	THCONR (λ)
	ϕ (%)	k (mD)	ϕ (%)	k (mD)	($\text{kJ m}^{-3} \text{K}^{-1}$)	($\text{W m}^{-1} \text{K}^{-1}$)
<i>Host rock (confining zones)</i>						
HF2	0.2–12.5	0.0001–0.94	2.4–24.1	3.2–128	2200–2600	2.10–3.00
HF3	1.2–10.2	0.0001–0.57	14.7–33.4	12–1308	2000–2500	1.20–2.10
HF4	1.6–15.3	0.0003–3.3	14.3–31.3	12–1940	1800–2300	1.00–1.60
HF7	0.9–8.0	0.0001–0.20	11.9–23.5	40–310	2000–2500	1.20–2.10
<i>Worked zones (Glasgow Ell and Main Coal)</i>						
Coal (HF8)	5.71	45.08	5.71	45.08	1304–1500	0.60–0.80
Backfill (HF9)	30.00	1000	30.00	1000	1200	2.40
Mine void (HF10)	91.84	1 350 000	91.84	1 350 000	4184	0.60

References

- Abesser C (2010) Open-loop ground source heat pumps and the groundwater systems: a literature review of current applications, regulations and problems. (OR/10/045) (Unpublished), British Geological Survey, Nottingham, UK, URL <https://nora.nerc.ac.uk/id/eprint/11706>
- Adams C, Balachander P, Banks D, et al (2026) The Future of Geothermal in the United Kingdom. In: Hollis C, Mackintosh S, Mayo F, et al (eds) The Future of Geothermal in the United Kingdom. Project InnerSpace, Boston, Massachusetts
- Adams R, Younger P (2001) A Strategy For Modeling Ground Water Rebound In Abandoned Deep Mine Systems. *Groundwater* 39(2):249–261. <https://doi.org/10.1111/j.1745-6584.2001.tb02306.x>
- Andrews BJ, Cumberpatch ZA, Shipton ZK, et al (2020) Collapse processes in abandoned pillar and stall coal mines: Implications for shallow mine geothermal energy. *Geothermics* 88:101904. <https://doi.org/10.1016/j.geothermics.2020.101904>
- Banks D (2012) An introduction to thermogeology: ground source heating and cooling, 2nd edn. Wiley-Blackwell, Chichester, West Sussex Somerset, N.J, <https://doi.org/10.1002/9781118447512>
- Banks D, Pumar FA, Watson I (2009) The operational performance of Scottish minewater-based ground source heat pump systems. *Quarterly Journal of Engineering Geology and Hydrogeology* 42(3):347–357. <https://doi.org/10.1144/1470-9236/08-081>
- Beynon S (2020) Geomechanical Properties of the Carboniferous Middle Coal Measures: Influence on fracture fluid flow and frictional stability during geothermal utilisation. NGR Core Sample Analysis, University of Liverpool, United Kingdom, URL <http://data.bgs.ac.uk/id/dataHolding/13607611>
- Bodeux S, Pujades E, Orban P, et al (2017) Interactions between groundwater and the cavity of an old slate mine used as lower reservoir of an UPSH (Underground Pumped Storage Hydroelectricity): A modelling approach. *Engineering Geology* 217:71–80
- British Geological Survey (2020) UK’s new underground observatory open for research. BGS Press, URL <https://www.bgs.ac.uk/news/uks-new-underground-observatory-open-for-research>
- Brook D (1994) Reclamation of Abandoned Underground Mines in the United Kingdom. In: International Land Reclamation and Mine Drainage Conference. American Society of Reclamation Sciences, Pittsburgh, PA, pp 163–171

- Brouyère S, Orban P, Wildemeersch S, et al (2009) The Hybrid Finite Element Mixing Cell Method: A New Flexible Method for Modelling Mine Ground Water Problems. *Mine Water and the Environment* 28:102–114
- Chandler MR, Mecklenburgh J, Rutter E (2023) The Role of Stress-Dependent Permeability in Minewater Geothermal Energy: Evidence from Laboratory Permeability Measurements. SSRN preprint, <https://doi.org/10.2139/ssrn.4611680>, URL <https://www.ssrn.com/abstract=4611680>
- Charalampidou EMC, Madankan M, Kardjilov N, et al (2023) Water flow within deformed and undeformed sample from Glasgow observatory. In: 2023 Mine Water Energy Symposium
- Chen Y, Voskov D, Daniilidis A (2025) Rigorous Numerical Methodology and Heat Recovery Analysis for Modeling of Direct Use Geothermal Systems. *Geoenergy Science and Engineering* 247:213661. <https://doi.org/10.1016/j.geoen.2025.213661>, URL <https://linkinghub.elsevier.com/retrieve/pii/S2949891025000193>
- Crooijmans R, Willems C, Nick H, et al (2016) The influence of facies heterogeneity on the doublet performance in low-enthalpy geothermal sedimentary reservoirs. *Geothermics* 64:209–219. <https://doi.org/10.1016/j.geothermics.2016.06.004>, URL <https://linkinghub.elsevier.com/retrieve/pii/S0375650516300517>
- Deeming KB, Dickie J, Roberts JJ, et al (2024) Nurturing a New Industry Rooted in Geoscience: Stakeholder Insights on Minewater Thermal in Scotland. *Earth Science, Systems and Society* 4(1):10121. <https://doi.org/10.3389/esss.2024.10121>, URL <https://www.lyellcollection.org/doi/10.3389/esss.2024.10121>
- Falcone G, Antics M, Baria R, et al (2017) Application of the United Nations Framework Classification for Resources (UNFC) to Geothermal Energy Resources - Selected case studies. No. ECE/ENERGY/110 in UNECE Energy Series 51, United Nations Economic Commission for Europe (UNECE), New York and Geneva
- Farr G, Busby JP, Wyatt L, et al (2021) The temperature of Britain’s coalfields. *Quarterly Journal of Engineering Geology and Hydrogeology* 54:14
- Freeze AR, Cherry JA (1979) *Groundwater*, 1st edn. Prentice-Hall, Englewood Cliffs, New Jersey, US
- Garg SK, Combs J (2015) A reformulation of USGS volumetric “heat in place” resource estimation method. *Geothermics* 55:150–158. <https://doi.org/https://doi.org/10.1016/j.geothermics.2015.02.004>
- Gillespie MR, Crane EJ, Barron HF (2013) Deep geothermal energy potential in Scotland. *Geology and Landscape, Scotland Programme Commissioned Report*, British Geological Survey, Nottingham, UK

- Gonzalez Quiros A, Macallister DJ, Macdonald A, et al (2024) De-risking green energy from mine waters by developing a robust hydrogeological conceptual model of the UK Geoenergy Observatory in Glasgow. *Hydrogeology Journal* 32:1307–1329
- Gonzalez Quiros A, Stewart M, Olver T, et al (2025) Challenges and opportunities for high-temperature mine thermal energy storage with focus on regulatory barriers for implementation. In: Valente T, Mühlbauer R, Ordóñez A, et al (eds) *International Mine Water Association Conference 2025 – Time to Come*. International Mine Water Association
- González Quirós A, Fernandez P (2019) Conceptualization and finite element groundwater flow modeling of a flooded underground mine reservoir in the Asturian Coal Basin, Spain. *Journal of Hydrology* 578:124036
- Greening B, Azapagic A (2012) Domestic heat pumps: Life cycle environmental impacts and potential implications for the UK. *Energy* 39(1):205–217. <https://doi.org/10.1016/j.energy.2012.01.028>, URL <https://www.sciencedirect.com/science/article/pii/S0360544212000333>
- Gringarten AC (1978) Reservoir lifetime and heat recovery factor in geothermal aquifers used for urban heating. *pure and applied geophysics* 117(1-2):297–308. <https://doi.org/10.1007/BF00879755>, URL <https://link.springer.com/10.1007/BF00879755>
- Guo P, Wang M, Dang G, et al (2023) Evaluation method of underground water storage space and thermal reservoir model in abandoned mine. *Rock Mechanics Bulletin* 2:100044
- Hall A, Scott JA, Shang H (2011) Geothermal energy recovery from underground mines. *Renewable and Sustainable Energy Reviews* 15:916–924
- Hamm V, Bazargan Sabet B (2010) Modelling of fluid flow and heat transfer to assess the geothermal potential of a flooded coal mine in Lorraine, France. *Geothermics* 39:177–186
- International Association for the Properties of Water and Steam (IAPWS) (2008) Release on the IAPWS Formulation 2008 for the Viscosity of Ordinary Water Substance. IAPWS Release R12-08, International Association for the Properties of Water and Steam (IAPWS)
- Kallesøe AJ, Vangkilde-Pedersen T (2019) Underground Thermal Energy Storage (UTES) – state-of-the-art, example cases and lessons learned. HEATSTORE project report, GEOTHERMICA – ERA NET Cofund Geothermal
- Kearsey T, Burkin J (2021a) Model metadata report for Glasgow Observatory post-drill bedrock and mine model. Publication - Report OR/21/017 (Unpublished), British Geological Survey, Nottingham, UK, URL <https://nora.nerc.ac.uk/>

[id/eprint/531157](https://nora.nerc.ac.uk/id/eprint/531157)

- Kearsey T, Burkin J (2021b) UKGEOS Glasgow post-drill coal mine model. NERC EDS National Geoscience Data Centre, <https://doi.org/10.5285/1F19A50C-B600-4F63-9512-E6C94F79D49C>, URL <https://www2.bgs.ac.uk/nationalgeosciencedatacentre/citedData/catalogue/1f19a50c-b600-4f63-9512-e6c94f79d49c.html>
- Kearsey TI, Receveur M, Monaghan AA (2024) Modelled hot sedimentary aquifer geothermal potential of Upper Devonian strata in the Midland Valley of Scotland. (OR/24/030) Open Report, British Geological Survey, Nottingham, UK, URL <https://nora.nerc.ac.uk/id/eprint/538341/>
- Khait M (2019) Delft Advanced Research Terra Simulator: General Purpose Reservoir Simulator with Operator-Based Linearization. PhD Thesis, Delft University of Technology
- Khait M, Voskov D (2018) Operator-based linearization for efficient modeling of geothermal processes. *Geothermics* 74:7–18. <https://doi.org/10.1016/j.geothermics.2018.01.012>, URL <https://linkinghub.elsevier.com/retrieve/pii/S0375650518300312>
- Loredo C, Roqueñí N, Ordóñez A (2016) Modelling flow and heat transfer in flooded mines for geothermal energy use: A review. *International Journal of Coal Geology* 164:115–122
- Monaghan A, Damaschke M, Starcher V, et al (2021) UKGEOS Glasgow GGC01 Final Borehole Information Pack. NERC EDS National Geoscience Data Centre, <https://doi.org/10.5285/E38C58A6-48EC-4AD1-A996-6C6144968D7D>, URL <https://www2.bgs.ac.uk/nationalgeosciencedatacentre/citedData/catalogue/e38c58a6-48ec-4ad1-a996-6c6144968d7d.html>
- Monaghan AA, Starcher V, Ó Dochartaigh B, et al (2019) UK Geoenergy Observatories: Glasgow Geothermal Energy Research Field Site: Science Infrastructure Version 2. (OR/19/032) (Unpublished), British Geological Survey, Keyworth, Nottingham, URL <https://nora.nerc.ac.uk/id/eprint/522814/>
- Monaghan AA, Bateson L, Boyce AJ, et al (2022a) Time Zero for Net Zero: A Coal Mine Baseline for Decarbonising Heat. *Earth Science, Systems and Society* 2(1):10054. <https://doi.org/10.3389/esss.2022.10054>, URL <https://www.lyellcollection.org/doi/10.3389/esss.2022.10054>
- Monaghan AA, Starcher V, Barron HF, et al (2022b) Drilling into mines for heat: geological synthesis of the UK Geoenergy Observatory in Glasgow and implications for mine water heat resources. *Quarterly Journal of Engineering Geology and Hydrogeology* 55(1):qjegh2021–033. <https://doi.org/10.1144/qjegh2021-033>, URL <https://www.lyellcollection.org/doi/10.1144/qjegh2021-033>

- Monaghan AA, Adams CA, Bell RA, et al (2026) Geological factors in the sustainable management of mine water heating, cooling and thermal storage resources in the UK. In: Gill C (ed) *Powering the Energy Transition through Subsurface Collaboration: Proceedings of the 1st Energy Geoscience Conference*. No. 1 in *Energy Geoscience Conference Series*, Geological Society of London, United Kingdom, p 17, <https://doi.org/10.1144/egc1-2023-39>, URL <http://dx.doi.org/10.1144/egc1-2023-39>
- Mouli-Castillo J, Van Hunen J, MacKenzie M, et al (2024) GEMSToolbox: A novel modelling tool for rapid screening of mines for geothermal heat extraction. *Applied Energy* 360:122786. <https://doi.org/10.1016/j.apenergy.2024.122786>, URL <https://linkinghub.elsevier.com/retrieve/pii/S0306261924001697>
- Muffler P, Cataldi R (1978) Methods for regional assessment of geothermal resources. *Geothermics* 7(2-4):53–89. [https://doi.org/10.1016/0375-6505\(78\)90002-0](https://doi.org/10.1016/0375-6505(78)90002-0), URL <https://linkinghub.elsevier.com/retrieve/pii/0375650578900020>
- Novikov A, Saifullin I, Hajibeygi H, et al (2025) A finite volume framework for the fully implicit thermal-hydro-mechanical-compositional modeling in subsurface applications. *Journal of Computational Physics* 538:114152. <https://doi.org/10.1016/j.jcp.2025.114152>, URL <https://linkinghub.elsevier.com/retrieve/pii/S0021999125004358>
- Oppelt L, Grab T, Ebel T, et al (2025) Mine Water as an Energy Source: Overview of Technical Basics, Existing Plants, and Monitoring Results. *Mine Water and the Environment* 44(3):519–543. <https://doi.org/10.1007/s10230-025-01057-w>, URL <https://doi.org/10.1007/s10230-025-01057-w>
- Orban P, De Paoli C, N'depo Y, et al (2024) Using old coal mines for geothermal energy: underground flow and heat transfer simulations as a pre-feasibility study in Liège (Belgium). In: *Geologica Belgica Luxemburg Congress*. SPW DGO4 - Service Public de Wallonie. Territoire, Logement, Patrimoine, Énergie, URL <https://hdl.handle.net/20.500.12907/51145>
- Payton RL, Fellgett M, Clark BL, et al (2021) Pore-scale assessment of subsurface carbon storage potential: implications for the UK Geoenergy Observatories project. *Petroleum Geoscience* 27(2):petgeo2020–092. <https://doi.org/10.1144/petgeo2020-092>, URL <https://www.lyellcollection.org/doi/10.1144/petgeo2020-092>
- Perez Silva J, McDermott C, Fraser-Harris A (2022) The Value of a Hole in Coal: Assessment of Seasonal Thermal Energy Storage and Recovery in Flooded Coal Mines. *Earth Science, Systems and Society* 2(1):10044. <https://doi.org/10.3389/esss.2022.10044>, URL <https://www.lyellcollection.org/doi/10.3389/esss.2022.10044>
- Pettigrew RP, Hussain R, McGarva RM, et al (2026) Borehole images: an under-utilized tool in ground investigations? *Geoenergy* 4(1):geoenergy2025–045. <https://doi.org/10.1144/geoenergy2025-045>, URL <https://www.lyellcollection.org/doi/10.1144/geoenergy2025-045>

- Raymond J, Therrien R (2014) Optimizing the design of a geothermal district heating and cooling system located at a flooded mine in Canada. *Hydrogeology Journal* 22(1):217–231. <https://doi.org/10.1007/s10040-013-1063-3>, URL <http://link.springer.com/10.1007/s10040-013-1063-3>
- Receveur M (2024) Investigating the key controls on mine water temperature in the United Kingdom. The University of Edinburgh, <https://doi.org/10.7488/ERA/4726>, URL <https://era.ed.ac.uk/handle/1842/42004>
- Receveur M, McDermott C, Fraser-Harris A, et al (2020) Key Controls on Mine-water Temperature in Flooded Mine Shafts: Insights from Temperature Profiles and Numerical Modelling. In: *Proceedings of the World Geothermal Congress 2020*, Reykjavik, Iceland, p 9, URL <https://www.worldgeothermal.org/pdf/IGAstandard/WGC/2020/15004.pdf>
- Renz A, Rühaak W, Schätzl P, et al (2009) Numerical Modeling of Geothermal Use of Mine Water: Challenges and Examples. *Mine Water and the Environment* 28(1):2–14. <https://doi.org/10.1007/s10230-008-0063-3>, URL <http://link.springer.com/10.1007/s10230-008-0063-3>
- Seidle J (2011) *Fundamentals of coalbed methane reservoir engineering*. PennWell Corp., Tulsa, Oklahoma
- Sevindik S, Spataru C, Domenech TA, et al (2021) A Comparative Environmental Assessment of Heat Pumps and Gas Boilers towards a Circular Economy in the UK. *Energies* 14(11):3027. <https://doi.org/10.3390/en14113027>, URL <https://www.mdpi.com/1996-1073/14/11/3027>
- Shorter K, MacDonald A, O Dochartaigh B, et al (2021) UKGEOS Glasgow Hydrogeological Test Pumping Data Release. NERC EDS National Geoscience Data Centre, <https://doi.org/10.5285/315C716A-8BC5-4071-AD67-62DA22E4B6AB>, URL <https://www2.bgs.ac.uk/nationalgeosciencedatacentre/citedData/catalogue/315c716a-8bc5-4071-ad67-62da22e4b6ab.html>
- Smith NT, Shreeve J, Kuras O (2020) Multi-sensor core logging (MSCL) and X-ray computed tomography imaging of borehole core to aid 3D geological modelling of poorly exposed unconsolidated superficial sediments underlying complex industrial sites: An example from Sellafield nuclear site, UK. *Journal of Applied Geophysics* 178:104084. <https://doi.org/10.1016/j.jappgeo.2020.104084>, URL <https://linkinghub.elsevier.com/retrieve/pii/S0926985119302836>
- Song G, Geiger S, Voskov D, et al (2026) Scenario-based data assimilation framework to improve production estimates for geologically complex geothermal reservoirs. *Geoenergy Science and Engineering* 263:214490. <https://doi.org/10.1016/j.geoen.2026.214490>, URL <https://linkinghub.elsevier.com/retrieve/>

- Spengler TSVG, Bruhn D, Daniilidis A, et al (2025) Co-Simulation of a District Heating and Cooling System in Combination with Mine Thermal Energy Storage. Master Thesis, PUSH-IT Project, Delft University of Technology, Delft, Netherlands, URL <https://resolver.tudelft.nl/uuid:fddf8633-cca5-4b4e-b0ea-1a148c5d7340>
- Starcher V, Monaghan A, Barron HF, et al (2021) Method and key observations from constructing a mine water heat subsurface observatory in Glasgow UK. (OR/21/020) (Unpublished), British Geological Survey, Nottingham, UK, URL <https://nora.nerc.ac.uk/id/eprint/530822/>, this item has been internally reviewed, but not externally peer-reviewed.
- Taco G, Kamenar A, Edgoose J (2020) Measurement of in-situ coal cleat compressibility. In: Proceedings of the 2020 Coal Operators Conference, Mining Engineering, University of Wollongong, p 15, URL https://ro.uow.edu.au/articles/conference_contribution/Measurement_of_in-situ_coal_cleat_compressibility/27686700
- Timur A (1968) An Investigation Of Permeability, Porosity, & Residual Water Saturation Relationships For Sandstone Reservoirs. The Log Analyst 9(04):10. URL <https://onepetro.org/petrophysics/article-abstract/171269/An-Investigation-Of-Permeability-Porosity-amp?redirectedFrom=fulltext>
- Todd F, McDermott C, Harris AF, et al (2024) Modelling physical controls on mine water heat storage systems. *Geoenergy* 2(1):geoenergy2023–029. <https://doi.org/10.1144/geoenergy2023-029>, URL <https://www.lyellcollection.org/doi/10.1144/geoenergy2023-029>
- UKGEOS (2025) Research Opportunities at the Glasgow Observatory. British Geological Survey, URL <https://www.ukgeos.ac.uk/opportunities-at-the-glasgow-observatory/science-challenges>, contains NERC materials © NERC 2026
- Voskov D, Saifullin I, Novikov A, et al (2024) open Delft Advanced Research Terra Simulator(open-DARTS). *Journal of Open Source Software* 9(99):6737. <https://doi.org/10.21105/joss.06737>, URL <https://joss.theoj.org/papers/10.21105/joss.06737>
- Wagner W, Kruse A (1998) Properties of Water and Steam / Zustandsgrößen von Wasser und Wasserdampf. Springer, Berlin, Heidelberg
- Walls DB, Banks D, Boyce AJ, et al (2021) A Review of the Performance of Minewater Heating and Cooling Systems. *Energies* 14(19):6215. <https://doi.org/10.3390/en14196215>, URL <https://www.mdpi.com/1996-1073/14/19/6215>
- Wang Y, Voskov D, Khait M, et al (2020) An efficient numerical simulator for geothermal simulation: A benchmark study. *Applied Energy* 264:114693. <https://doi.org/10.1016/j.apenergy.2020.114693>, URL <https://linkinghub.elsevier.com/retrieve/pii/S294989102600134X>

- Wang Y, De Hoop S, Voskov D, et al (2021) Modeling of multiphase mass and heat transfer in fractured high-enthalpy geothermal systems with advanced discrete fracture methodology. *Advances in Water Resources* 154:103985. <https://doi.org/10.1016/j.advwatres.2021.103985>, URL <https://linkinghub.elsevier.com/retrieve/pii/S0309170821001408>
- Wang Y, Voskov D, Daniilidis A, et al (2023) Uncertainty quantification in a heterogeneous fluvial sandstone reservoir using GPU-based Monte Carlo simulation. *Geothermics* 114:102773. <https://doi.org/10.1016/j.geothermics.2023.102773>, URL <https://linkinghub.elsevier.com/retrieve/pii/S037565052300127X>
- Wyllie M, Rose WD (1950) Some Theoretical Considerations Related To The Quantitative Evaluation Of The Physical Characteristics Of Reservoir Rock From Electrical Log Data. *Journal of Petroleum Technology* 2(04):105–118. <https://doi.org/10.2118/950105-G>, URL <https://onepetro.org/JPT/article/2/04/105/161943/Some-Theoretical-Considerations-Related-To-The>
- Yang P (2016) Investigation of the Geomechanical Behavior of Mine Backfill and its Interaction with Rock Walls and Barricades. PhD Thesis, École Polytechnique de Montréal
- Younger PL, Robins NS (2002) Challenges in the characterization and prediction of the hydrogeology and geochemistry of mined ground. Geological Society, London, Special Publications 198:1–16
- Zhang L, Dieudonne AC, Daniilidis A, et al (2025) Thermo-hydro-mechanical modeling of geothermal energy systems in deep mines: Uncertainty quantification and design optimization. *Applied Energy* 377:124531
- Ó Dochartaigh BE (2009) A scoping study into shallow thermogeological resources beneath Glasgow and the surrounding area. Tech. rep., British Geological Survey, Nottingham, UK