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Toward Net-Zero Targets: Waste Heat and Geothermal for Interseasonal Heat Storage and Heat Recovery in District Heating

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Why you should attend

- Minewater heat recovery offers a scalable, low-carbon pathway for district heating and cooling, supporting the UK Net Zero target.
- Coupling minewater systems with industrial waste heat enables subsurface heat replenishment and seasonal thermal storage, improving long-term efficiency.
- Numerical modelling shows that abstraction–recharge balance and subsurface complexity strongly control thermal performance; quantifying these uncertainties reduces deployment risk and supports investment decisions.

Abstract

This study examines the essential elements required to effectively incorporate minewater into district heating and cooling network systems. Utilizing minewater for heat recovery presents a low-carbon energy option for both heating and cooling purposes enabling progress towards the United Kingdom's net zero objective. Furthermore, it has the potential to offer valuable thermal storage capabilities, particularly beneficial for addressing inter-seasonal variations in demand. Geothermal systems are often associated with significant risks and costs, posing a challenge in identifying the most suitable areas for their effective implementation. This research expands upon a prior feasibility study conducted in Barnsley, Yorkshire, which investigated the development of a comprehensive heat network incorporating heat, power, and mobility elements while harnessing waste heat from a glass factory. The current study concentrates on analysing subsurface factors such as flow rate, yield, mine void volume, and interconnectivity that directly influence the flow patterns and thermal characteristics of the accessible minewater. A 3D model was developed using Petrel software, incorporating data from available boreholes and Mining Remediation Authority maps to characterize subsurface conditions. Based on this model, a numerical simulation in Eclipse and Petrel was used to explore various scenarios and assess the impacts of different engineering configurations. The aim was to match designs to different demand scales, allowing for testing of hydraulic, geochemical, and other geological parameters, thereby identifying the optimal operational approach for efficient and sustainable extraction of heat or cooling, including consideration of thermal storage. The results provide quantification of uncertainties associated with key subsurface parameters to reduce risk and thus encourage investment towards system deployment. The study indicates that heat recovery from minewater can offer significant benefits towards meeting carbon reduction targets. While in large-scale schemes, the temperature of the reservoir and surrounding rocks gradually decreases, leading to a reduction in efficiency, integrating minewater with waste heat in a heat storage concept could replenish the heat level and maintain the system's efficiency over the long term.

Keywords: Waste heat, Minewater heat, District heating, Heating and cooling, Geothermal energy, Net-Zero, Heat storage

1. Introduction

To achieve the UK Net Zero target by 2050, an average of approximately one million homes per year must transition to low-carbon heating technologies from 2026 to 2050. However, a wholesale replacement of existing heating systems with heat pumps or hydrogen boilers alone is unlikely to secure universal adoption across the UK's 25 million homes, due to technical, economic, and social constraints [1]. In parallel, the quantity of low-grade waste heat from sources including but not limited to data centres, supermarkets, and industrial facilities is increasing due to population growth, market expansion, and technological and industrial development. Capturing, storing, and reusing this waste heat during periods of high seasonal demand represents a significant opportunity to improve overall energy system efficiency. Geothermal energy constitutes a vast and largely underutilised resource, and the use of water-filled abandoned mine workings offers a capable pathway to access thermal systems. By storing industrial waste heat within mine water geothermal schemes, thermal efficiency can be improved while reducing subsurface temperature losses and supporting low-carbon heat supply.

The complex interplay of mining techniques, interconnectivity, and subsurface physical properties within underlying formations greatly influences fluid flow within reservoirs, making the prediction and management of production plans challenging. Hence, a comprehensive understanding of flow behaviour is required for optimizing production plan. The connectivity between coal seams is critical for achieving optimal recovery and significantly influences reservoir performance, however, incorporating all fractures and man-made roadway networks into standard reservoir simulators can be computationally prohibitive.

This research introduces a robust mathematical model for fluid flow simulation, specifically addressing the flow behaviour of mine water in heat recovery processes within a 3D space. As for subsurface reservoirs, inherent complexity characterizes the subsurface, encompassing both natural formations and man-made structures such as mines. This complexity arises from the variable rock properties and interconnections between the rock formations, exerting significant influence on fluid flow dynamics. Although comprehension of flow behaviour is needed from the integration of various geological, geophysical, and engineering data sources for designing an efficient heat recovery system.

The mathematical model used is Eclipse for flow modelling, based on the finite volume method. To streamline computational efficiency, the study analysed the available data and then prioritised the parameters with the most impact in the model. A submersible pump is employed to extract mine water from a saturated excavated coal mine for heat recovery purposes. Subsequently, a positive displacement pump injects the thermally utilised water into a shallower coal mine with naturally lower temperatures.

This simulation process primarily involves resolving mass, momentum, and energy conservation equations, which vary depending on the complexity of the adopted physical model. For instance, in simpler shallow systems, models often rely solely on Fourier's Law for heat conduction, assuming homogeneous media. Conversely, porous and fractured media models are utilized in more intricate simulations, particularly in larger spatial scales such as reservoir engineering analyses and require numerical models [2]. The analysis needs an interdisciplinary assessment to evaluate suitable system characteristics and sustainability, as illustrated in Figure 1.

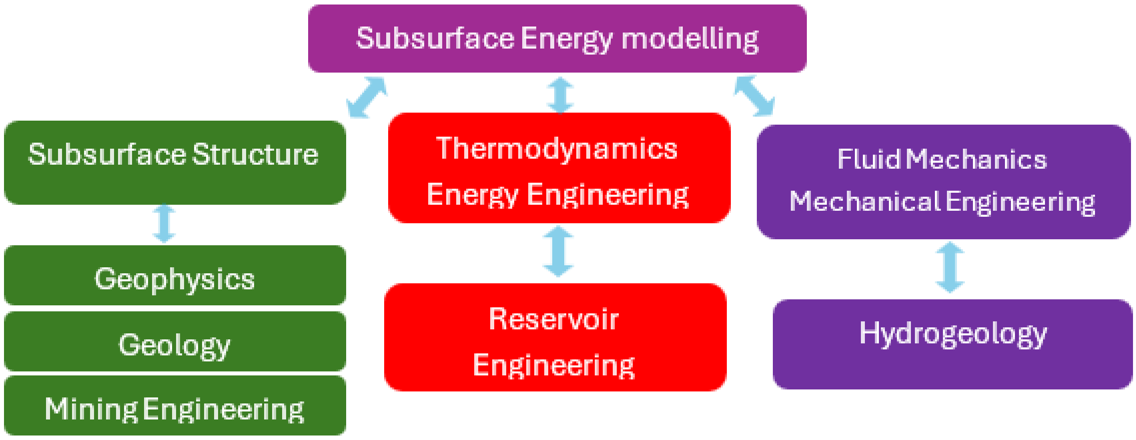

Figure 1:Overview of the interdisciplinary model for analysing system characteristics and sustainability

In industry, for instance, some stakeholders prioritize only the geological and geophysical aspects, disregarding the environmental impact and, notably, variations in power plant efficiency. Economic concerns often take precedence.

2. Using minewater for waste heat storage and heat recovery

This study investigates the viability of utilising and storing waste heat in the minewater to meet inter-seasonal demand variations in Barnsley, South Yorkshire. Abandoned mines represent a promising opportunity for tapping into geothermal energy sustainably. Once excavated coal seams, termed "panels," are left with residual voids that gradually fill with natural water flow [3]. Consequently, coal seams offer a renewable geothermal reservoir primarily suited for building heating or cooling applications. A comprehensive study undertaken in Barnsley, South Yorkshire demonstrated the potential to extract up to 7MW of heat from a glass manufacturing facility, alongside the utilisation of abandoned mine workings for heat storage and recovery. This investigation revealed that such an approach is both practical and economically advantageous [4]. In the initial design concept, the mine water functions as a mechanism for seasonal heat storage, providing additional support and replenishment to the primary energy source, which consists of industrial waste heat.

Figure 2 illustrates the concept of the heat recovery and heat storage process. Mine water available in the Barnsley coal seam, located approximately 278 m below ground level and at a temperature of 20 °C, is abstracted and used for space heating of buildings (left-hand side). After heat extraction, the water temperature is reduced to approximately 13 °C and the cooled water is then reinjected into the Winter seam at a depth of 139 m below ground level, where the natural formation temperature is also around 13 °C.

Continuous heat extraction from the Barnsley seam results in a reduction in subsurface temperature over time. To restore the thermal balance, a nearby glass manufacturing facility (right-hand side) utilises the 13°C mine water for industrial cooling. The warmed return water, at approximately 20°C, is subsequently reinjected into the Barnsley seam, where it is stored for use during colder seasons.

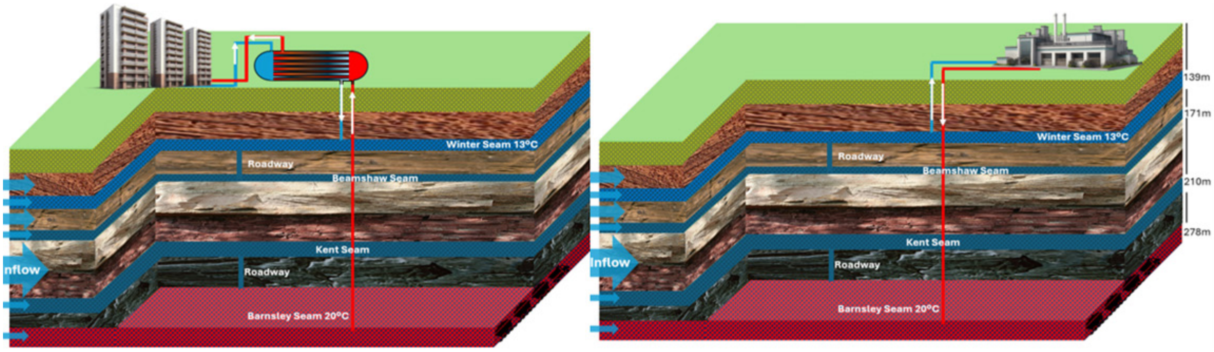

Figure 2: Schematic of mine water energy system showing heat recovery (left) and heat storage schemes (right).

3. Model functionality: a descriptive overview

A numerical model was built to comprehensively assess the energy potential of local minewater, as well as system efficiency and the influence of key parameters such as flow rate over time. The primary objective of this model is to quantify the range of water flow within local seams under various abstraction scenarios, while also evaluating the effects of factors such as interconnectivity, mine geometry, and subsurface conditions on flow and thermal behaviour. Such analyses are instrumental in identifying the optimised engineering configuration for efficient heat recovery and heat storage schemes. In this study, the model integrated three key components to estimate thermal behaviour (Fig 3)

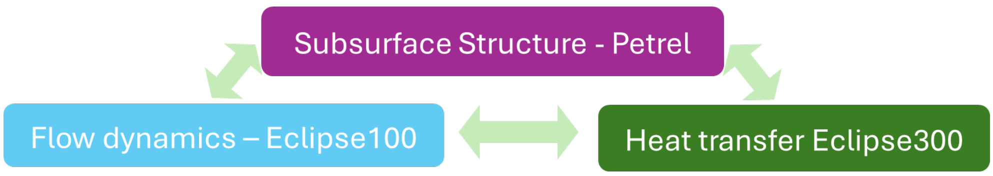

Figure 3: Key elements of subsurface modelling

3.1. Model calibration in geothermal reservoir management

For the case study, input data was sourced from local records like depth, temperature, water level, historical borehole data, maps, and logs. The methods used for interpreting and validating these data have been documented in the two papers referenced as [3] and [5].

3.2. Subsurface structure

Firstly, a structural representation was developed in Petrel to present subsurface conditions. Groundhog software, British Geology Survey (BGS), was used to visualise borehole data and to help create a simplified 3D subsurface model, enabling consistent interpretation of the subsurface structure and stratigraphy. This was subsequently utilised to construct a 3D grid model in Petrel refining the interpretation from available log data [3]. Critically, mine working maps for each specific coal provided depth, facilitating improved correlation between wells [4]. This information is critical for estimating void volume, capacity, transmissivity, and flow behaviour in subsequent flow modelling stages. Figures 4A–F illustrate the process by which depth data, geological information, mine maps, and physical properties are integrated to construct a numerical model in Petrel.

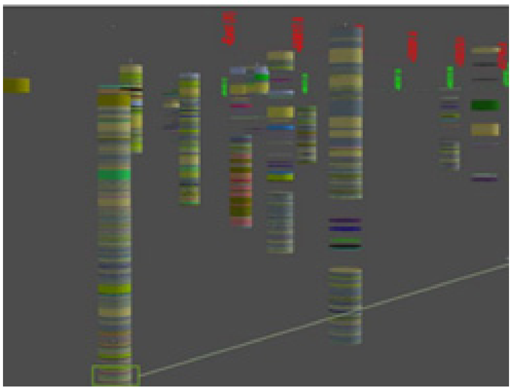

Figure 4A: Digitised boreholes using Groundhog. Colours show different lithology.

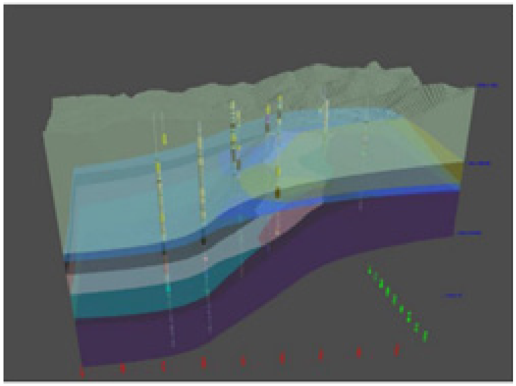

Figure 4B: A simplified 3D model from correlating the borehole data.

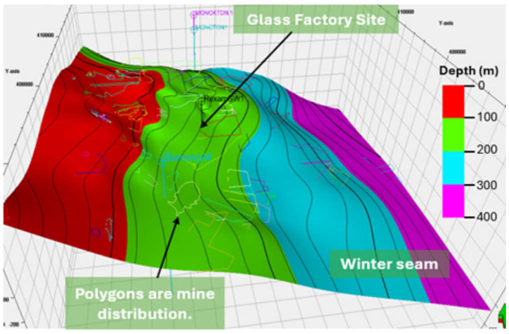

Figure 4C: 3D mineworking panels distribution in Winter seam.

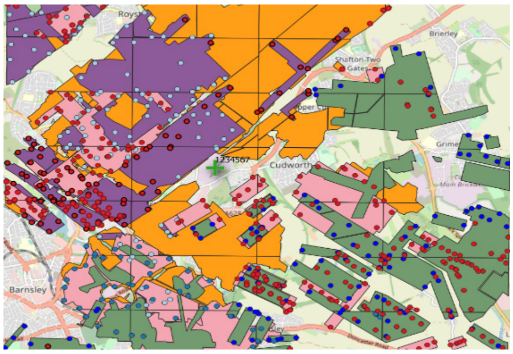

Figure 4D: 2D mineworking panels distribution in the area from mine maps. (colours represent mines in different coal seam)

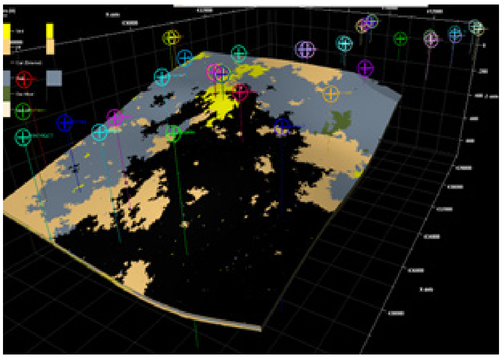

Figure 4E: Model from top Winter Seam showing lithology variation around the mine (black colour).

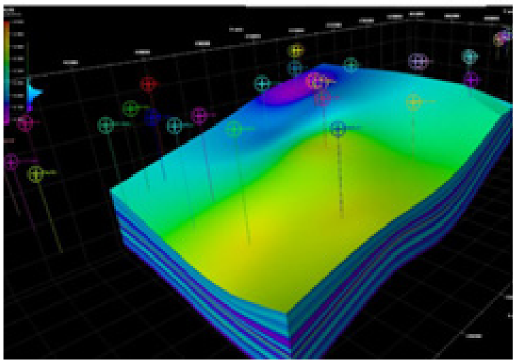

Figure 4F: Porosity model, Winter Seam - cold.

3.3. Numerical simulation and assumptions of flow and heat transfer in mines

The storage capacity of subsurface systems depends on the available void volume within excavated mines, roadways, surrounding rock, and faults. Approximately half of the excavated mine volume and nearly the entirety of roadway volumes consist of void space, enabling fluid flow with minimal resistance due to the high permeability induced by anthropogenic mining activities. In contrast, void space within natural rock formations is significantly lower and varies with lithology. Fluid flow in low-permeability formations such as shale is highly restricted compared with sandstone, owing to extremely low permeability, limited pore connectivity, and poor transmissivity. Consequently, abandoned mines represent a highly valuable resource for large-scale subsurface heat storage and heat recovery applications.

The majority of mines in the Barnsley seam were developed using the "Room and Pillar" method, an older conventional mining technique commonly used in South Yorkshire. In contrast, the mines in the Winter seam were excavated using a combination of "Longwall" and "Room and Pillar" techniques (MRA Interactive Map Viewer). In the Room and Pillar method, approximately 48% of the original seam volume was typically extracted, increasing to around 60% with the introduction of fully mechanised processes [6]. In Longwall mining method, extraction rates reached up to 90%, resulting in significant post-mining collapse. These mines were excavated separately, with varied geometries, as illustrated. The excavation thickness typically slightly exceeds the seam thickness, while in mechanised Longwall mining, it averages between 3 and 5 m [7]. Given that the average thickness of the Barnsley coal seam is approximately 2.5 m, an average excavation thickness of 3 m was assumed for the mines.

In this model, the primary focus was on analysing water flow within both the roadways and the mine workings, as well as the associated heat transfer processes between the fluid and the surrounding rock formations. For the three-dimensional model, the following factors were considered: the size, length, and spatial distribution of the underground roadway sections; the temperature of the surrounding rock; inlet and outlet water temperatures; and the thermophysical properties of the fluid.

This model enabled the calculation of the heat storage capacity of the abandoned mine and an analysis of the energy efficiency of the geothermal system under various operational conditions, while also assessing its impact on the overall mining life cycle. While the model does not incorporate fracture spaces resulting from mining activities, the roadway space was conceptualized as a porous media model to reduce modelling complexity and improve computational efficiency. Thus, the model effectively encompasses the majority of the underground water storage areas within abandoned mines.

3.4. Boundary and initial conditions

Thermal boundary conditions encompass a range of scenarios, including heat transfer across the model and conditions where there is no heat exchange. In terms of conserving mass flow rates, boundary conditions are employed to mimic natural phenomena such as recharge rate, regional flows, and abstraction or injection from boreholes in subsurface structures. Initial conditions signify the system's state at the beginning of a simulation, which may include factors like thermal gradients, pressure distributions, or hydraulic head levels. The simulation assesses how the ground's temperature reacts when boundary conditions are applied. The comprehensive temperature response of ground heat exchange changes over time, with varying heat rejection or extraction sequences, and it is subsequently determined through spatial and temporal overlays. The reliability of the results generated by such software depends on the accuracy of the geometric configuration and boundary conditions applied to the specific case under analysis [2]. Table 1 displays some of the parameters specified in the initial conditions.

Table 1: Initial condition parameters

Elements	Depth m	Porosity (%)	Permeability (mD)	Temperature (ºc)	Pressure (Barsa)
Abstraction Point/ Barnsley Seam	240-243	50	2500	20	26.53
Injection point/Winter Seam	90-93	50	2000	13	9.1
Beamshaw Seam	120-123	50	2200		12.3
Kent Seam	180-183	50	2200		17.86
Roadways Winter to Beamshaw Seam	92-121	0.9	-		
Roadways Beamshaw to Kent Seam	122-181	0.9	-		
Roadways Kent to Barnsley Seam	182-271	0.9	-		
Virgin Rock / shale to Sandstone range	Out of coal seams	11-25	0.1-70		
Material	Density (kg/m3)	Viscosity (Pa\cdotps)	Thermal Conductivity (W/m.ºC)	Specified Heat Capacity (J/kg.ºC)	Geothermal Gradient (ºc/m)
Water	1025	0.001	0.61	4200	
Rock	2600		2.1	900	0.032

The simulated study area covers a surface extent of 4 × 4km and extends to a depth of approximately 300 m below ground level. The domain is discretised into 13 geological layers, and a total of nine distinct material types are represented in the model.

The Winter seam is located at a depth of 139 m below ground level and has a natural temperature of approximately 13°C. The Barnsley seam, which acts as the primary heat source, is situated at a depth of 278m and has a temperature of around 20°C. The Winter seam is hydraulically connected to the Beamshaw seam, located ~70m deeper, through a roadway with a diameter of 3m. Beamshaw is subsequently connected to the Kent seam, positioned at a depth of 210m below ground level, via a separate roadway. The Kent seam is further connected to the Barnsley seam through an additional roadway (see Figure 2).

Permeability values for virgin rock formations range from 0.5 to 100 mD, reflecting materials from low-permeability shale to highly permeable sandstone. Porosity values range from 0.09% to 0.25% for virgin rocks, 0.9 for roadways, and 0.5 for excavated coal seams.

For the initial conditions, hydrostatic pressure is assumed to vary with depth, while the initial temperature field is defined using monitored temperature data obtained from the Rexam borehole at the glass factory.

4. Water level results and comparison with pumping station operation

The simulation duration spans seven months to comprehend reservoir dynamics, followed by continuous operation over a span of 25 years, with 70% of the time operating at full capacity. The scenario involves high production-extraction rates, with an extraction rate of approximately 50 l/s.

The findings indicate a direct correlation between the abstraction rate and the drop in pressure, signifying a corresponding decrease in water level (Figure 5). Should the abstraction rate exceed the recharge rate, the system's depletion would be inevitable, rendering the scheme unsustainable. The rate at which the system dries up hinges on several factors, including the mine seam's geometry and size relative to the abstraction rate, connectivity to other water sources via roadways, and the aquifer's strength. In this design, the system is configured to abstract water at various rates until the pressure reaches a critical threshold of 78 psi. At this pivotal juncture, pumping ceases to allow water to replenish, after which pumping resumes. The disparity in pressure denotes the hydrostatic pressure, derived from the weight of water above, and can be correlated with water level using hydrostatic pressure equation:

$$H_P = \rho g h + P_{atmosphere} \quad (1)$$

$$\Delta h = \frac{\Delta P}{\rho g} \quad (2)$$

Where HP is total pressure, ρ represents the density of the fluid, h represents the height of the fluid column, g is gravity, $P_{atmosphere}$ is the atmospheric pressure, and Δh is the drawdown.

A physical pumping test has not yet been conducted at this site. However, observations from experimental pumping tests conducted under similar conditions in another location in Gateshead have been compared to the model results. The comparison revealed similar behaviour, albeit with a slight variance in drawdown, likely attributable to the presence of a stronger local aquifer in Gateshead (Figure 5). As expected, the water level exhibits a rapid initial decline and then tends towards stabilisation as the system approaches equilibrium; however, increases in the abstraction rate temporarily accelerate drawdown at each stage.

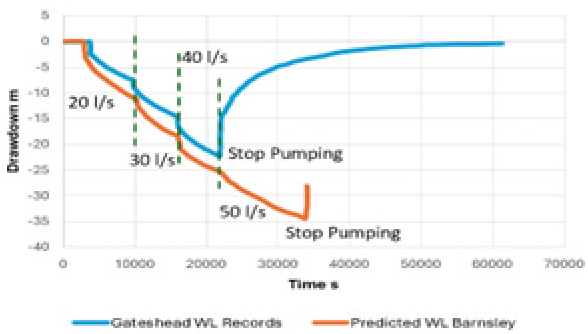

Figure 5: Drawdown as a function of flow rate: modelled results for Barnsley (orange) compared with observed water levels in Gateshead (Mining Remediation Authority, 2023).

5. Thermal Discussion

At an abstraction rate of 50 l/s, water at 20 °C is extracted from the Barnsley seam, located approximately 278 m below ground level. Subsequently, a marked reduction in temperature is observed. In figure 6 the long-term temperature reduction over a 25-year heat recovery period belongs to abstraction zone. Initially, the system exhibits near steady-state thermal behaviour, as the abstracted water is primarily replenished from within the remaining extent of the Barnsley coal seam, thereby maintaining a similar temperature. After that temperature dropped by 1.6°C during the first year as result of heat extraction, followed by a more gradual decline at a reduced rate, 1.4°C over the following 24 years. This temperature decline is attributed to a decrease in mine pressure, with pressure differentials acting as the primary driver of flow. As the pressure within the coal seam decreases, water from alternative sources migrates toward the abstraction point. Gravity and pressure gradients drive inflow from overlying coal seams with lower temperatures through unoccupied mine roadways, which occurs more rapidly than lateral inflow from external aquifers at comparable depths and temperatures. This progressive temperature reduction adversely affects the efficiency of surface heat recovery. Heat loss continues until the system reaches a threshold at which heat extraction becomes inefficient or incompatible with the surface infrastructures.

The dominant inflow source in this mine is a coal seam located approximately 70 m above the abstraction level, with a temperature of 16°C, connected via a major roadway. Additional roadways, connections to shallower formations, or direct hydraulic communication between the heat source and cooler zones would further increase heat loss and reduce recovery efficiency [8]. Although such connections enhance recharge in terms of flow rate, higher flow rates are also associated with increased thermal losses, which are undesirable. Therefore, the selection of an appropriate abstraction location requires a careful balance between recharge and extraction. Excessive inflow can lead to significant heat loss, whereas over-abstraction or insufficient recharge may result in thermal depletion of the resource.

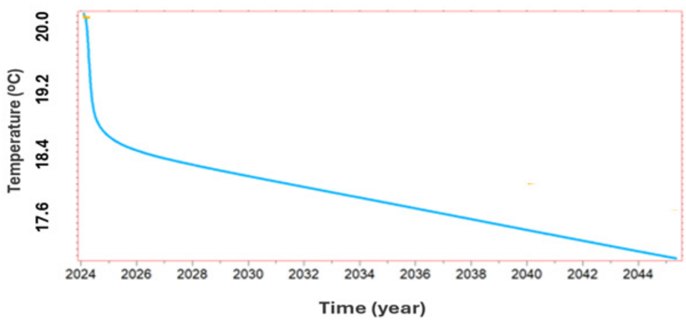

Figure 6: Temperature variation in 25 years of heat recovery.

To investigate the impact of heat recovery on a large scale, the entire coal seam should be examined rather than just the abstraction point. The model revealed that heat recovery on this large scale can affect the entire coal seam over time, albeit not immediately. Within the first six months, the area up to nearly 100 meters away from the abstraction point and even the other connected coal seam experienced significant effects. However, the impact diminishes gradually as we move further away from the point, and there is no substantial heat loss beyond the lateral geometry of the mine. This is attributed to the water's ability to balance the pressure drop much more efficiently and rapidly via the flow through roadways than via water from the aquifer within the virgin rocks (Figure 7). In the long term, a larger area will be thermally affected, gradually leading to the cooling down of the entire excavated mine, albeit at different rates.

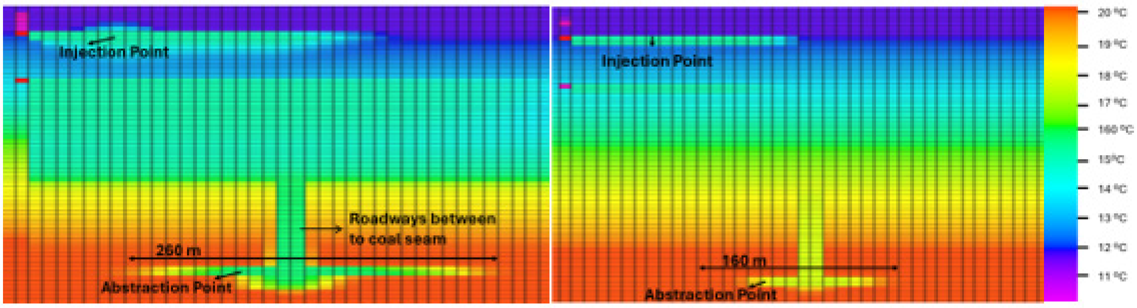

Figure 7: Temperature distribution after 25 years heat recovery (left) vs 6 months heat recovery (right).

6. Conclusion

This study presents quantitative results for a proposed minewater heat recovery and thermal storage scheme in Barnsley, Yorkshire, using an integrated modelling approach to evaluate the system performance over an extended time frame of 25. The work demonstrates the suitability of Petrel software for quantifying coupled flow and thermal behaviour in minewater systems. Although originally developed for hydrocarbon reservoir simulation, the software effectively addresses the interdisciplinary requirements of this study, involving subsurface interpretation, fluid flow, and thermal processes. The modelling required detailed analysis of mine workings alongside the local geological and hydrogeological framework.

The simulation is shown to be a cost-effective and efficient method for evaluating subsurface responses to alternative heat recovery, storage strategies, and production management scenarios. As with conventional reservoir modelling, the reliability of the results is dependent on data availability, data quality, and the correct representation of initial and boundary conditions. These uncertainties are expected to reduce as additional information becomes available from future well installations and pumping tests. For the Barnsley case study, modelling has enabled quantification of complex minewater flow behaviour within anthropogenic subsurface conduits.

The results showed that the natural influx is sufficient to sustain abstraction rates of up to 50 L/s. However, the dominant contribution of inflow from colder sources results in a progressive reduction in reservoir temperature over time. This thermal decline can negatively impact heat recovery efficiency and may lead to incompatibility with surface system design, a behaviour consistent with observations from other large-scale minewater schemes.

Maintaining an appropriate balance between abstraction and recharge is therefore critical. Higher inflow rates are associated with increased thermal losses, which may compromise long-term system sustainability through cooling of the heat source. To mitigate this effect, integration of minewater systems with supplementary heat sources, such as industrial waste heat, offers a potential pathway to elevate subsurface temperatures and enable seasonal thermal storage. In the Barnsley context, wastewater from existing glassworks represents a practical example. Such integration would allow excess heat to be stored during warmer periods and recovered during colder seasons, effectively transforming the subsurface system into a geobattery and enhancing the overall performance of minewater heat recovery.

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About the author

Eshagh Goudarzi is a researcher in sustainable energy systems, with a focus on district heating and cooling, subsurfacethermal storage, and waste heat recovery. His work integrates thermo-hydraulic modelling, aquifer and mine-water systems, and energy system optimisation to enhance the efficiency and resilience of low-carbon heating and cooling networks. He has professional experience in the oil and gas industry and later joined a heating and cooling research group during his PhD at London South Bank University, where he focused on data-driven analysis of smart heating and cooling systems.