A Case Study of the Integration of Minewater into Smart Cooling and Heating Network systems

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Abstract
Minewater presents a significant opportunity as an energy source and store in the UK and elsewhere. This research investigates the feasibility and factors necessary to successfully integrate minewater into smart cooling and heating network systems that can support acceleration towards the UK's net zero target. Heat recovery from minewater offers a low-carbon source of energy for either heating or cooling and can provide thermal storage, potentially valuable for inter-seasonal demand. The work builds on a feasibility study in Barnsley, Yorkshire, which explored the design of a heat network that integrates heat, power, and mobility and uses waste heat from a glass factory. This work focusses on analyzing the subsurface factors including flowrate, yield, mine void volume, and interconnectivity, which affect the flow and consequently thermal behavior of the available minewater. A 3D model using Petrel and Groundhog have been created combining data from the available boreholes and Coal Authority maps to characterise the subsurface conditions.

Keywords: Minewater, Heat Recovery, Waste Heat, Heat Storage, Geothermal Energy.

1.0 Introduction to the role of minewater in a smart heat network
Heat decarbonisation is the most challenging priority in Europe's energy sector in the following decades (1). To achieve net zero by 2050, heating, cooling, electricity, and transportation should be combined to balance these different demands in a smartly controlled way called Smart Local Energy System (SLES) (3). Statistically, heat accounted for 50% of global energy consumption (40% in the UK) and produced 40% of global CO_2 emissions (4). In 2021 only 21.5% of total energy was generated from sustainable resources in the UK (5) and water from abandoned mines is a possible heat source. As a result of the 1970s oil crisis, the UK government reconsidered the national energy policy to develop renewable sources (6). As a result of the closing of mines and consequently pumping stations, the abandoned mines flooded, which led to environmental issues including land contamination. Numerous research studies conducted in the 1990s aimed to comprehend the system and were published on the topics of water treatment, geochemical analysis of minewater, and hydrogeology (7). Ultimately, the potential value of this relatively warm water at a constant temperature throughout the year was recognised along with opportunities for economic rejuvenation of mining communities. The UK Coal Authority recently reviewed over 30 potential large heat networks in the UK (8). Two such projects are under development in northeast England, in Gateshead and Seaham Garden Village and two more are planned in South Tyneside and Caera, South Wales. These schemes will supply heat as a source of energy in a smart heating network.

A heat network is a reliable low-cost heat distribution system to reduce CO_2 emissions. It can take advantage of excess energy like waste heat from the industry where individual solutions cannot (10). In 2018, operational heat networks in the UK amounted to 13,995 and generated 17.7 TWh of heat and 1.9 TWh of cooling (11). Recovering low-grade heat from any local resources including geothermal heat can increase the efficiency of heat pumps on networks. The government estimates that heat networks could save approximately 70% on carbon emissions compared to gas boilers and 80% on cooling compared to air conditioning (11).

Projects at Markham in Derbyshire and at Caphouse colliery in Wakefield were the earliest minewater examples in South Yorkshire. In Markham, minewater was pumped from a depth of 234.5 mbgl (meter below ground level) at 15^{o}C and a flowrate of 3 l/s through a heat exchanger, for heat recovery, connected to a 20KW heat pump. In 2015, the submerged pump relocated to a shallower depth at 170.5 mbgl (12), which improved the efficiency due to a lower pumping cost. A pump abstracts water from a depth of 171 mbgl. A 10KW heat pump was applied to extract 5^{o}C heat from minewater at 14^{o}C. To date, there have been no reported issues of long-term decline in temperature regarding thermal feedback of reinjected water to the abstraction point. This may be due to the low flowrate compared to the large diameter of the shaft or due to water movement inside the well caused by pumping (13).

Gateshead, which commenced operations in 2021, is the first-ever large-scale shallow Minewater Geothermal Energy Scheme (MGES) in the UK. The plan was to produce 6 MW of energy to heat 1600 buildings and to save 1800 tonnes of CO_2 emissions annually. Five boreholes out of 10 drilled wells were found to be functional for abstraction and injection (14) from three main sites. Three abstraction wells were drilled to depths of 110–124 mbgl, and three reinjection wells were drilled to a depth of 155 mbgl from one site, Abbotsford-Road. The design assumed that the minewater temperature would be lowered by 4°C (11°C to 7°C) using a heat pump with a Coefficient of Performance (COP) of 4. The rate of heat extracted, $H_{ex,}$ based on the water flowrate is calculated as below:

$$H_{ex}=Q.\rho.c.\Delta T$$

Where: Q (l/s) is Flowrate, ρ is density, c is water specific heat capacity (kJ/l/k), and ΔT (^{o}C) is the temperature change.

The Rate of heat supplied H_{Supply} is:

$$H_{Supply} = \frac{Hex}{(1-\frac{1}{\mathrm{COP}})}$$

The design required nearly 107 l/s minewater to supply the site's maximum 2.4 MW HP capacity. The project license allows for an abstraction rate of 49 l/s; however, the current abstraction rate is only 20-30 l/s from one borehole. The other two abstraction boreholes failed to operate due to low yields. One of the three reinjection boreholes was unable to absorb enough reinjected water. The surface engineering system was unable to operate at >30% capability due to unrealistic subsurface flowrate expectations and inadequate machinery design (15). Larger equipment required more power thus the efficiency decreased (14). Later, a new abstraction well was drilled to 131 mbgl with the injection well depth at 280 mbgl. This time a 1.2 MW HP with COP of 4 was set to abstract heat from 13°C water. While 50 l/s of water was required to service the complete capacity of 1.2MW HP, pumping tests demonstrated the possibility of 60-70 l/s. Since May 2021, the site has abstracted 40 l/s continuously. Even though the main abstraction well offers 60-70 l/s, again two extra boreholes failed to operate (15). In summary, the main challenges faced by the UK's largest minewater scheme were large variations in borehole performance, low subsurface absorption/abstraction rates, inadequate geological and hydrogeological information, and an oversized heat pump. Large international projects, such as Heerlen in the Netherlands (16), Asturian Central Coal Basin in Spain (4), Bochum in Germany (17), and Springhill in Nova Scotia, Canada (15), have each demonstrated that a comprehensive investigation of geological/hydrogeological properties, interconnectivity, and man-made parameters is critical to understanding subsurface behaviour. Moreover, a structural model helps to minimize the risk of failure.

Geothermal energy is currently considered a costly high-risk source of energy. However, its large storage capacity and significant CO2 emissions reduction capability make minewater schemes a sustainable energy source. Figure 1 illustrates the level of CO2 emissions reduction in the largest UK minewater projects compared to international schemes. Seaham and Gateshead are compared to the average UK boiler CO2 emissions, but the comparison sources for the other projects are not specified.

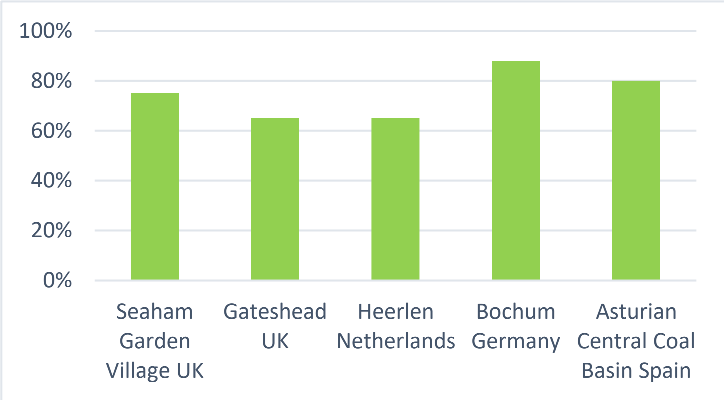


Figure 1: Co_2 Emissions reduction compared to gas boilers.

2.0 Integration of waste heat and minewater for heat recovery and storage purposes

Previous studies indicate that 66 to 70% of primary energy is wasted (18), and heat energy is the most easily dissipated form of energy. This research explores the feasibility of recovering and storing waste heat in mine water for inter-seasonal variation demands in Barnsley, South Yorkshire.

2.1 History of mining in the UK

After the industrial revolution in the 19th century, the demand for coal rose significantly until 1913 when UK coal extraction reached nearly 290 million tonnes per annum (20). Coal was the primary source of energy until the 1960s with more than 200 million tonnes produced annually from the mines, and 25% of the UK's buildings lying above one of 23,000 abandoned coal mines (8,23). Between the 1950s and 1990s, the mines were deemed uneconomic and were closed. These mines could potentially produce 2200 TWh of heat, while the UK demand is 300TWh annually (23). Figure-2 shows the location of abandoned mines in the UK.

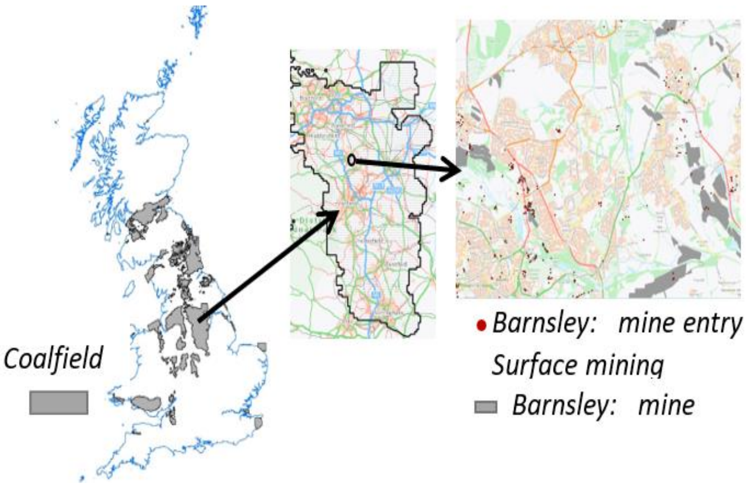


Figure 2: UK mine distribution (CA), South Yorkshire & Barnsley.

2.2 Concept

These abandoned mines can serve as a geothermal energy source. The coal seams that were previously extracted, also known as "panels," have become partially empty spaces that got filled with natural water flow after pumping operations ceased. The water in these seams is heated by the geothermal energy of the rock formations, and the temperature increases with depth based on the local geothermal gradient (23). Therefore, coal seams offer a renewable geothermal resource that can be used mainly for heating or cooling buildings.

Figure 3 illustrates the concept of heat recovery. The colour represents temperature, showing blue changing to red with increasing depth/temperature. High-temperature water from flooded abandoned mines is pumped and circulated through a heat exchanger, then transferred into a heat pump for secondary heat transfer. The heat pump optimises the temperature required for use in heat networks. In storage mode, low-temperature water from shallow seams is extracted and circulated through a heat exchanger to absorb waste heat, and then stored in a deeper hotter seam for inter-seasonal usage. In this way, cold water can be utilized for industrial cooling systems.

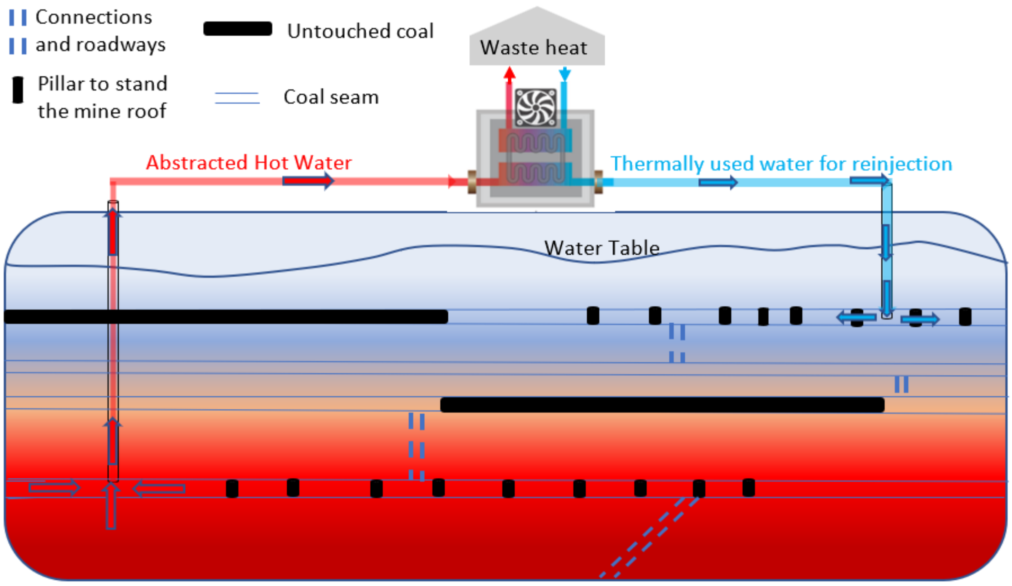


Figure 3: Schematic for the proposed energy from minewater scheme.

3.0 Main parameters and impacts

To minimise the risk of failure, a comprehensive understanding of subsurface structures is necessary. The water flow can originate naturally from an underground aquifer or from surface drainages such as rivers and lakes. The flow is primarily determined by rock properties. Porosity, which is the proportion of intergranular space in the lithology, controls the void volume and therefore the amount of water that a particular subsurface rock type can hold. Groundwater can be found where porosity exists, but water flow depends on permeability, pore shape, and connectivity. An aquifer is defined as a body of rock or unconsolidated sediment with sufficient permeability to allow water to pass through it. It is important to map the subsurface strata, man-made structures, and their interconnectivity to assess the adequacy of high-rate water abstraction and absorption in potential MGE schemes.

The volume of void space also depends on the compaction of the strata, mining type, and post-mining conditions. Therefore, assessing void space requires information on local mining history and recent conditions. The flow through abandoned mines is strongly influenced by the mineworking layout. Longwall and Room-and-Pillar mining are the main excavation techniques, and each affects void space differently (7). In addition, there are kilometres of lateral roadways that connect the worked seams and are used for safety, ventilation, haulage, and maintenance access.

"Room-and-Pillar" was the primary method used in Barnsley until the 1950s, with extracted volume typically around 48% of the original seam volume and has the highest rate of void volume (7). The longwall technique became popular in the UK since the 1950s due to a higher extraction rate of up to 90%. Because of the high extraction rate, the mine would have collapsed after cutting. Nevertheless, the resulting permeability in these collapsed flooded panels is relatively high. Figures 4A and 4B illustrate the pattern of both techniques.

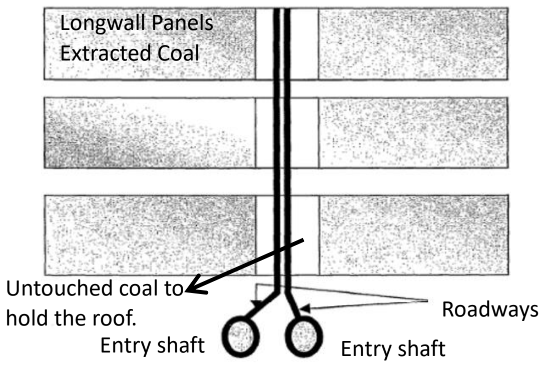


Figure 4A: Longwall mining technique (7).

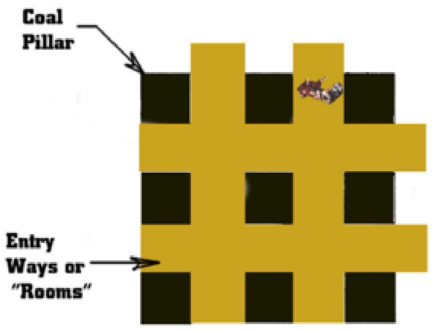


Figure 4B: Room and Pillar mining.

There is a wide range of regional estimates for the overall void space in abandoned mineworking, depending on mining technique and local geology. For intact old mines with a lower rate of mine extraction, Gluyas et al. (2020) suggest 50% residual void space (10). In Barnsley, a conservative estimate of 15% void volume is recommended by the Coal Authority (2). The main question is how much void space is hydraulically connected to the mineworking panels. These mines are formed of discrete panels at different depths and are connected to each other by roadways and tunnels. Roadways are usually absolute void spaces, and where a complete map exists, the flow behaviour in mines can be predicted with confidence. Generally, the volume of these roadways has been estimated as 10% of the total void volume of the working panel.

4.0 Opportunities in Barnsley, South Yorkshire

4.1 Location and characteristics of Barnsley mines

Barnsley lies above the South Yorkshire coalfield and has a rich history of mining. In this region, 25 major coal seams are recognised with a gentle easterly dip (2). There are thousands of abandoned mineworking panels in these coalfields, along with a complex network of shafts, roadways, and tunnels. Figure 5A illustrates the study area, which is focussed on the glassworks - a potential source of waste heat - building on the results of the GreenSCIES study (19). This feasibility study (area of 8kmx7km), which is centred on the glassworks, estimates that 7 MW of waste heat from the glassworks, along with heat recovery from mine water, could potentially heat 1800 buildings that are connected in a heat network (19). Figure 5B displays the seams identified in this area, based on the Wharncliffe Woodmoor colliery, and highlights the way they are hydraulically connected (based on a study provided by Barnsley Metropolitan Borough Council).

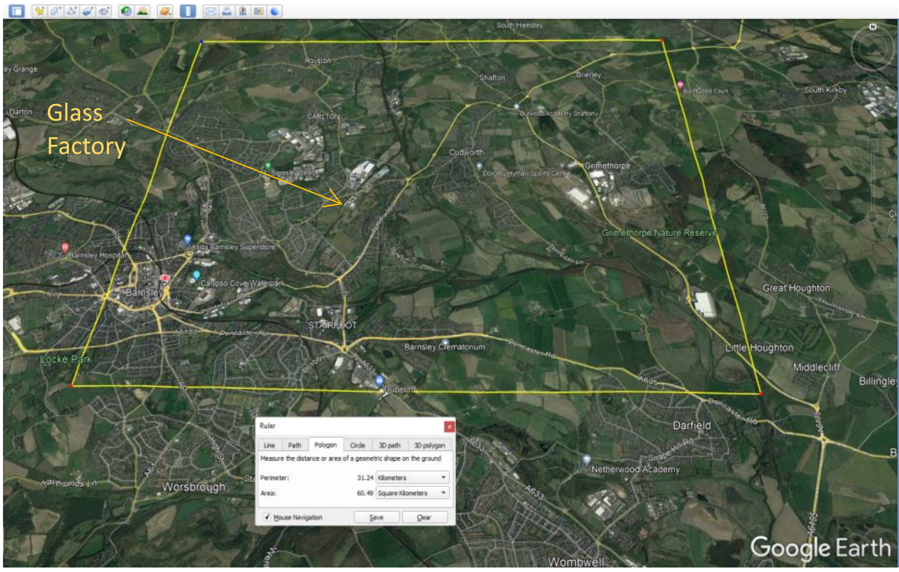


Figure 5A: Area of study is shown in left-hand side (google maps).

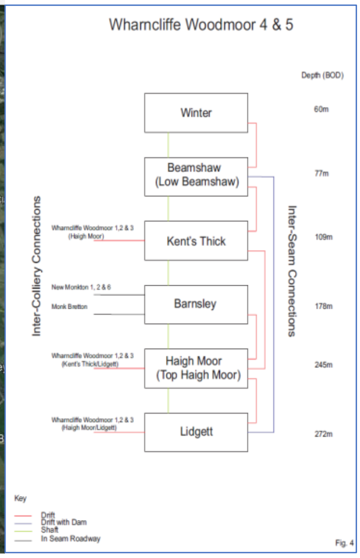


Figure 5B: Seams connectivity.

Initial analysis of temperature measurements carried out for BMBC as part of the GreenSCIES study has confirmed an encouraging high-temperature gradient of 30°C/km, which is one of the highest in the UK (9).

4.2 Concept applied to Barnsley

The glass factory operates 24/7 at high temperatures. Continuous temperature monitoring, as part of the GreenSCIES study, showed an average temperature of 28°C from the heating water and estimated 7 MW of heat available for recovery (19). In this study, Barnsley Main, which is one of the thickest coal seams located at a depth of 245-255 mbgl beneath the glassworks, was identified as a source of heat and a heat store. It is one of the most extensive coal seams in the region with a temperature of 18.2°C verified by nearby shafts. The concept is summarized in Figure 6A. The Beamshaw and Winter seams, which are hydraulically connected, are proposed as the source from which to extract heat. These seams are the shallowest coal seams below the water table, which results in lower pumping costs at the temperature of 13°C. Although higher temperatures increase the HP efficiency, extracting hotter water from deeper layers requires more energy, leading to higher electricity costs and a decrease in the overall system efficiency. A balance between temperature and depth could enhance efficiency. These seams are the most efficient flooded seams. In the summer season, when cooling is delivered to the factory through a heat exchanger, the extracted heat would be injected into Barnsley Main for inter-seasonal storage. This heat will be recovered when needed in cold seasons (Figure 6B).

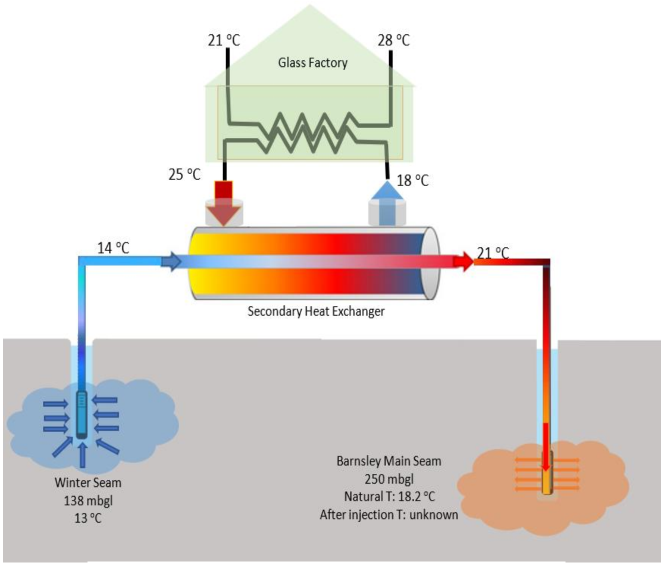


Figure 6A: Barnsley summer design.

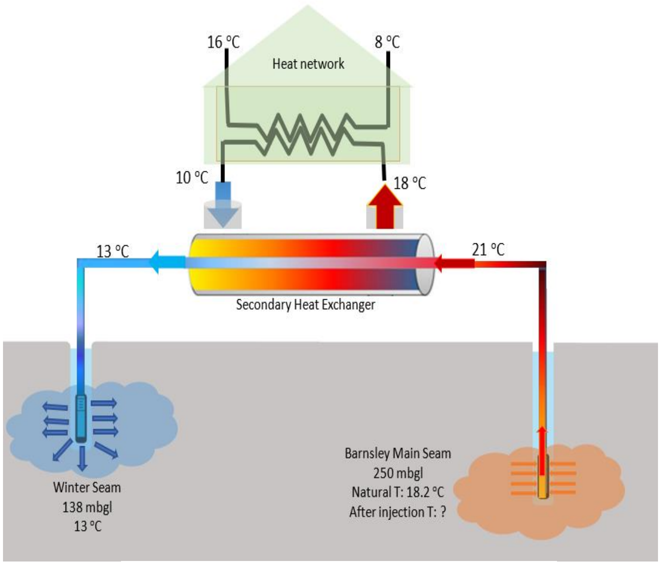


Figure 6B: Barnsley winter design.

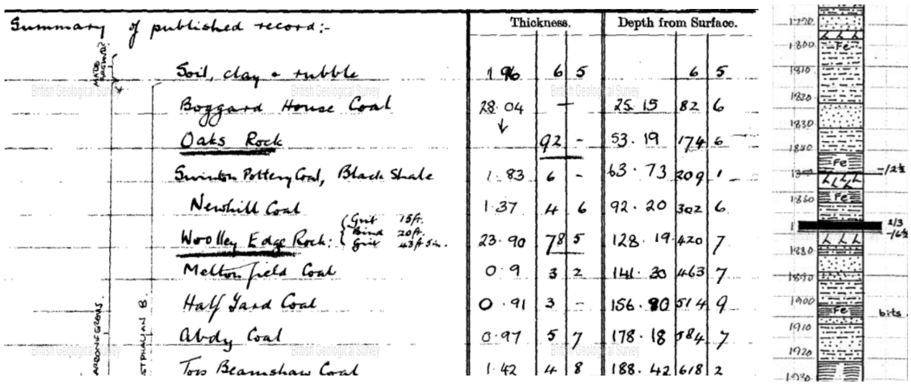
4.3 The challenges associated with the application

Although there are plenty of opportunities for a project like this in Barnsley, there are challenges related to licensing, the state of the mineworking, data issues, and local conditions. Drilling to the exact point for injection or abstraction purposes is challenging for thin seams. The Winter seam is located close to the water table. Once the submerged pump starts operating, the water level will drop rapidly until it stabilizes at the static water level (24). The distance between these levels is known as drawdown. For the Winter seam, there is a risk that the mine drying up. While abstracting water from the shallowest seam may provide an opportunity for highly efficient abstraction, it may not last for a long time. A significant proportion of workings are recorded in very old records, lacking enough details for accurate void volume or connectivity estimation.

4.4 Data gathering and methodology

To understand the subsurface conditions, a wide range of data was collected from BGS borehole records and historical maps and archives, including scans of mine workings, shaft records, pumping records, and local reports, principally from the Coal Authority (CA). These records provide the history of the mine and are critical for borehole planning. Water level, annual temperature, and other local observations are recorded for some wells by BMBC. There are also reports from local authorities that help to provide a better understanding of interconnectivity and flow expectations. All data can be integrated using software to generate a data-based model of the subsurface conditions. The aim is to identify the best locations for abstraction/injection purposes and provide quantitative limits on the available void volume for heat storage and heat recovery. The British Geological Society's (BGS) Groundhog is modelling software that can be used to interpret geological and environmental data and visualize a model in both 3D and 2D subsurface displays.

In total, 45 wells distributed across the target area and penetrating the 25 main coal seams have been reviewed. Lithological information and geological classification, physical properties, and thickness variations have been taken from BGS records, although not all wells have a complete record. Figure 7 provides an example borehole record showing a typical stratigraphic description and summary log dated 1869. Regional bedrock maps were also used, and there are some valuable regional correlations available from 18th-century reports.



Summary of published record:-	Thickness.			Depth from Surface.		
Soil, clay & rubble	1 96	6	5		6	5
Boggard House Coal	28 04			25 15	82	6
Oaks Rock		92	-	53 19	174	6
Swinton Pottery Coal, Black Shale	1 83	6	-	63 73	209	1
Newhill Coal	1 37	4	6	92 20	302	6
Woolley Edge Rock: {Grit 15ft. Bind 20ft. Grit 43ft 5in.	23 90	78	5	128 19	420	7
Melton field Coal	0 9	3	2	141 30	463	7
Half Yard Coal	0 91	3	-	156 80	514	9
Abdy Coal	0 97	5	7	178 18	584	7
Two Beamshaw Coal	1 42	4	8	188 42	618	2

Figure 7: Example of borehole data recorded from 1896 (BGS)

Figure-8 shows the digitised strata and thicknesses of layers in different boreholes. On the right-hand side, an example of expected transmissivity was modelled based on typical lithological properties. Sands and abandoned mines have the highest transmissivity while clay has the least.

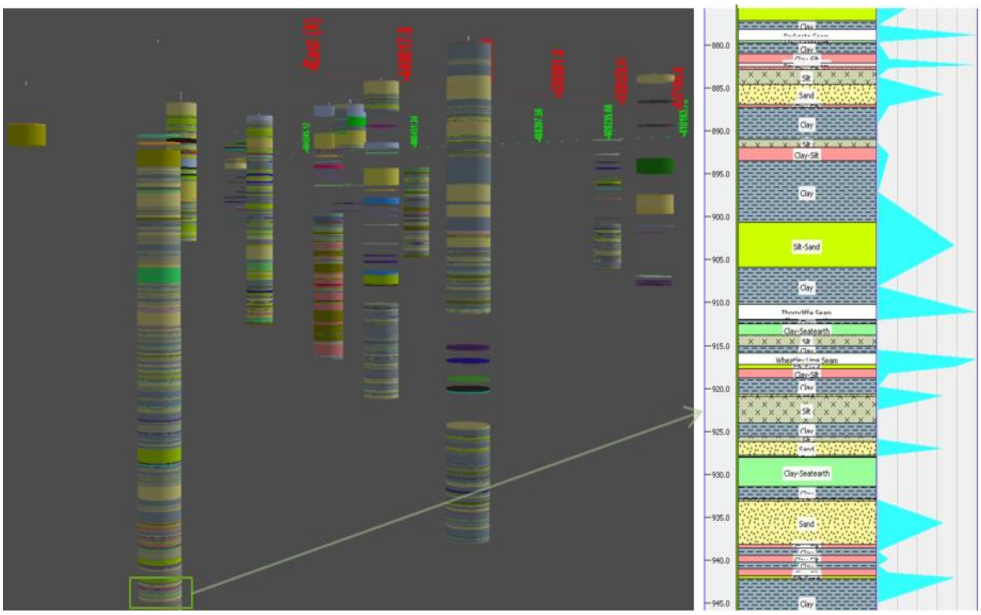


Figure 8: Digitised boreholes using Groundhog. Nature of strata vs depth vs transmissivity in light blue. Colours show different lithologies.

A 3D model was formed to visualize the subsurface geometry (Figure-9). The structural model allows estimates of abandoned mines' volume, connectivity, and the feasibility of 7MW heat recovery.

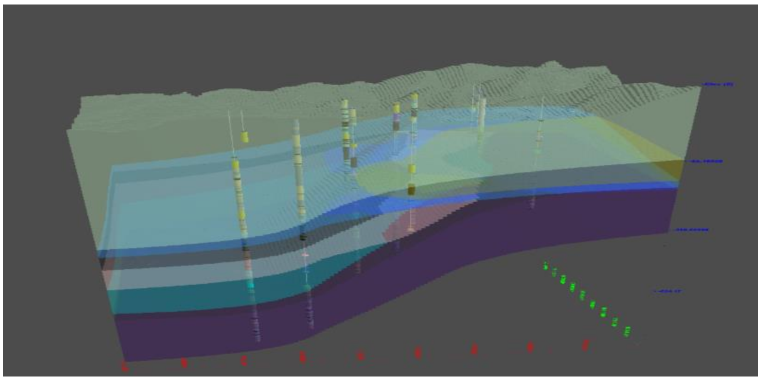


Figure 9: A simplified 3D model from the borehole data. Colours represent subsurface formations.

5. Initial investigation of capacity and feasibility in Barnsley

This section analyses and discusses the demand, feasibility, opportunities, and future steps related to the subject at hand.

5.1 Heat demand in Barnsley and UK

For the proposed scheme of 7616 dwellings, an annual heat demand of 63,647 MWh is required, and an additional 8 MW of heat is needed to support peak heat demand (19). This additional heat could be provided by utilizing stored waste heat in abandoned mines. Figure 10 illustrates the seasonal variation in heat demand for UK buildings, which is averaged in Figure 11 and compared to a constant mean. This shows that heat can be stored for 6 months and used during the other 6 months.

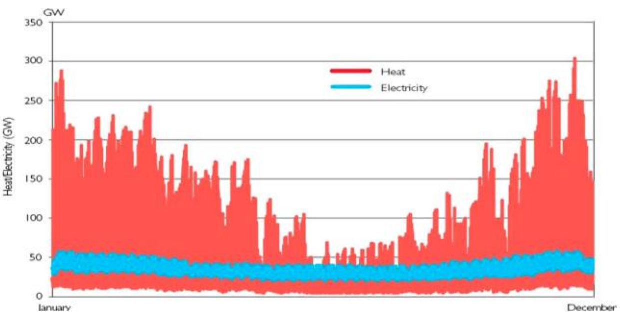


Figure 10: Seasonal variation in half-hourly heat demand for UK buildings (DECC, 2012)

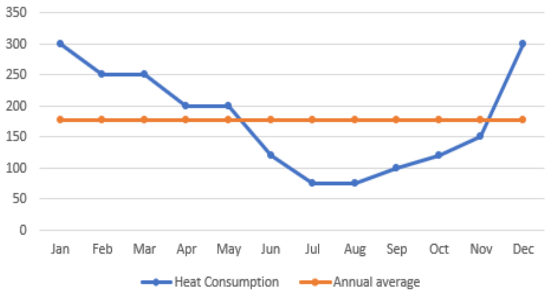


Figure 11: Annual heat consumption vs average annual het demand

5.2 Void space analysis comparing supply and demand.

"Storing 7 MW of heat requires a large volume of water and void space. The amount of energy that can be extracted by a heat pump is estimated using the following formula:

$$H=Q^{*}\Delta\Theta^{*}C_{w}$$

Where: Q is the flowrate (l/s), ΔΘ is the temperature difference between the input and output of the heat pump (ºC), and C_w is water specific heat capacity J/k/l (13). The required flowrate to support 7MW heat based on temperature difference is displayed in Figure-13. This high-rate requires sources in high-transmissivity layers like sandstones, faults, and abandoned mines.

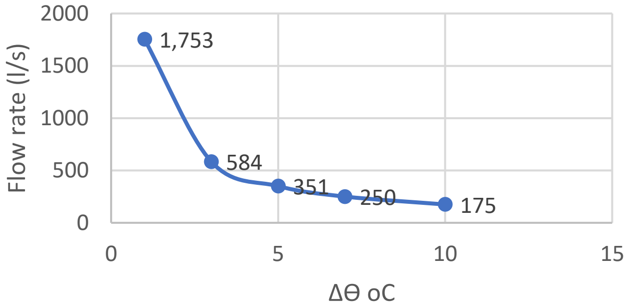


Figure 13: Required flowrate for storing 7MW of heat.

For the proposed operation's heat storage source (Barnsley Main seam), the seam thickness averages 2.5 meters, and the temperature can reach over18ºC. The recorded water level confirms that the shallowest flooded seam below the area is Winter, at a depth of 138 mbgl. The volume of mineworking panels in each seam has been determined by integrating the available data, combined in a 3D model shown in Figure-14.

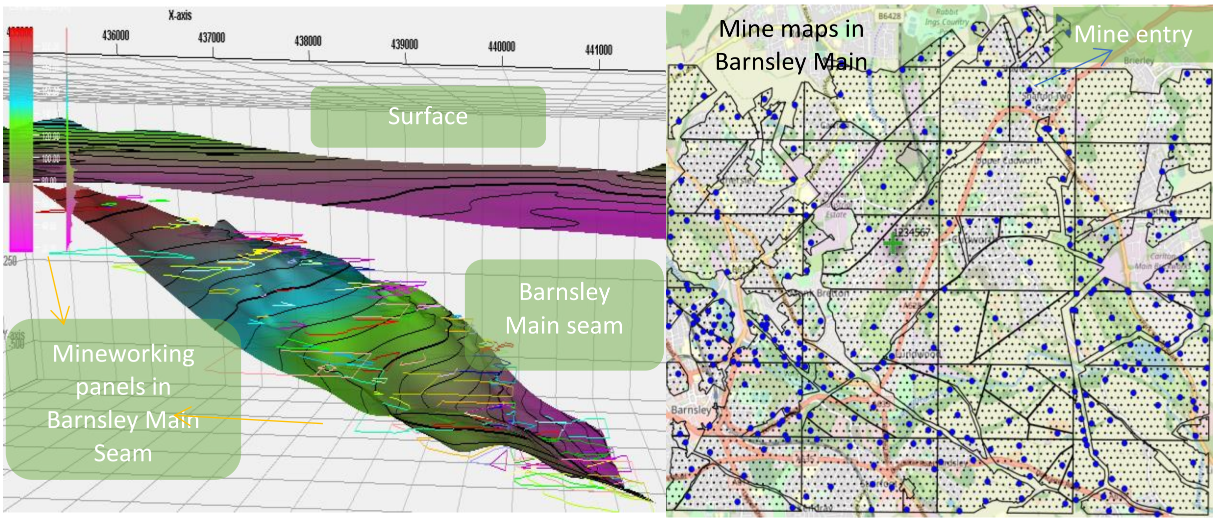


Figure 14: Mineworking panels in Barnsley main seam, right 2D, left, imported to 3D grid model and interpolated.

The volume of the mineworking in the Winter seam, the cold source, was estimated to be 13.1M.m^3, while the Barnsley Main seam is considerably larger with a volume of 92.5M.m^3. Assuming that the system is operational 70% of the time during the 6 storing months due to maintenance issues and demand limitations, a minimum void volume of 3.87 M.m^3 of water is required for storage in abandoned mines if 5ºC of heat is extracted during circulation. There is some uncertainty in the void volume estimate. Mines worked after 1949 are expected to be collapsed due to the high-rate excavation in the Longwall technique, while older mines are partially collapsed. The roadways and connections could also be blocked at some points. Figure 15 shows estimates of the required mine volume in Barnsley's seams for a range of parameters. Winter and Barnsley volumes are compared with the required mine volume from the worst-case scenario (only 10% void volume) to the most probable situation (20% available void volume).

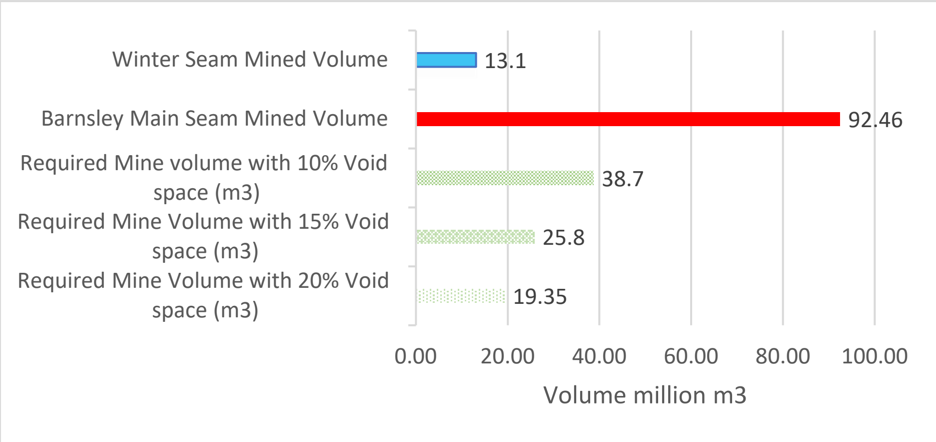


Figure 15: Modelling mine volume for ΔΘ=5°C.

The graph indicates that the Barnsley Main seam is capable of carrying the required amount of water, while the Winter seam is too small. Figure-16 compared the potential continuous pumping rate from the Winter seam over 6 months with different void spaces and heat transfer scenarios. The orange colour represents the available flowrate from the Winter seam, while the blue indicates the amount of additional flowrate required to support a 7MW of energy in each scenario.

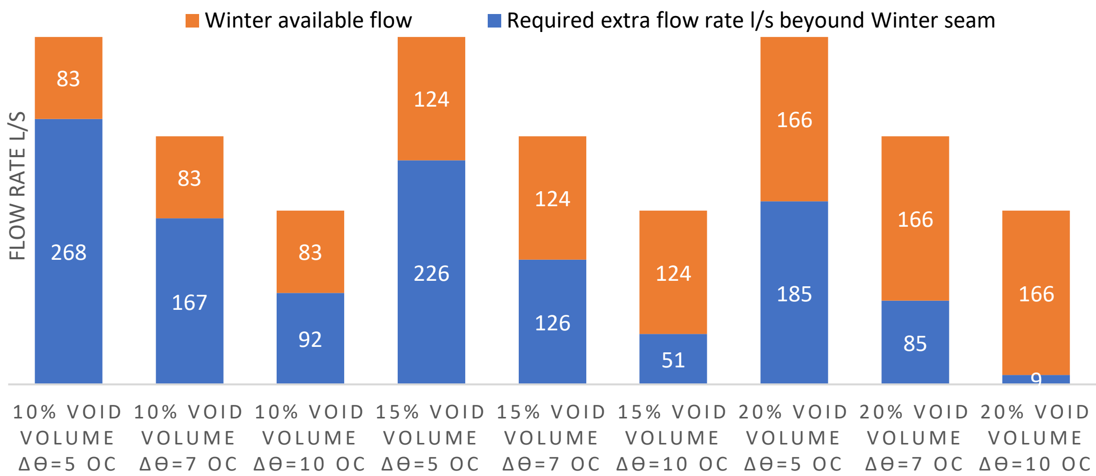


Figure 16 Winter seam: Additional abstraction flowrate to support 7mw HP.

5.3 Analysis of combining coal seams

The Winter seam alone is insufficient to support a 7 MW heat scale project. However, the next shallowest coal seam below Winter is the Beamshaw seam, located at 171 mbgl. The Winter and Beamshaw seams are connected at Wharncliffe Woodmoor 4&5, the local colliery in the area (refer to Figure 5). The volume of mineworking panels in the Beamshaw seam was analysed, and the total volume of the Beamshaw and Winter seams was compared to the required mine volume in Figure 19. The analysis shows that the two connected seams together can provide sufficient volume annually for heat recovery and storage purposes.

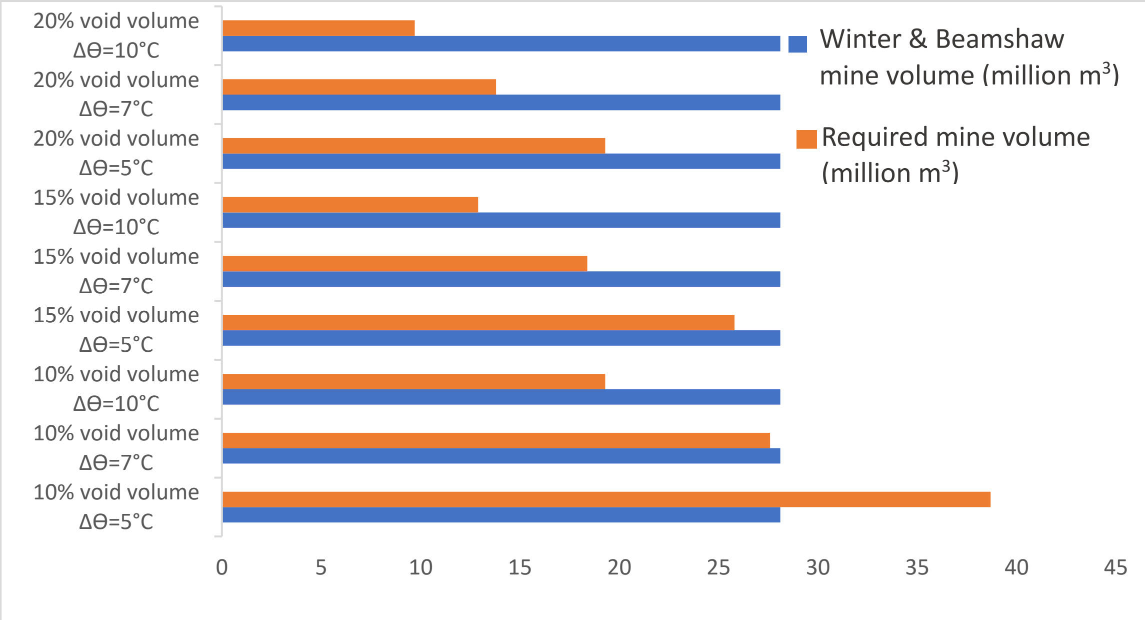


figure 19: Winter & Beamshaw mine volume vs required mine volume.

6. Conclusion

This paper reports results from the first part of a new comprehensive approach to examine the operation of smart local energy systems involving minewater for a case study in Barnsley, South Yorkshire. The work builds on a feasibility study in the area which showed that recovering up to 7MW from glass manufacturing and using the old mine workings as a means of storing and recovering heat is feasible and can be economic. In the original concept, the mine water allows for seasonal storage of heat and provides back-up and top-up to the main energy source, industrial waste heat. Recovering 7MW waste heat requires a significant amount of water. Flooded abandoned mines are relatively permeable compared to untouched subsurface formations, and the Barnsley mines present a high pumping rate opportunity. To minimize costs, a minimum number of wells is desirable.

In this study, data from sources across a range of disciplines, maps and historic records, logs, and relevant research have been analysed in detail to build a model of the subsurface initially for consideration of void space. The approach demonstrates the value of combining the data into a single model, using all the available information, for example, taking account of the historic variation in workings between Room-and-Pillar and Longwall mining. Key parameters of the proposed scheme can be tested from this data-based model. The work shown explored the likelihood of different worked seams in the area to meet the proposed scale of local demand, i.e., to recover 7MW of heat energy. The results indicate the following:

- The Barnsley Main seam appears to be sufficiently large, with connected workings, making it a strong candidate for locating a warm water source and possible storage.
- The shallow Winter seam proposed as a cold source for balancing the scheme, requires additional volume which may be met locally by the Beamshaw seam, which is hydraulically connected to the Winter seam, and thus doubles the capacity.
- A well into the deeper Beamshaw seam offers the advantage of gravity helping to draw water from Winter to Beamshaw seam while pumping.
- The overall system efficiency may drop because of higher pumping costs in deeper seams. However, such a scheme could potentially heat 1800 residential buildings.

This model has been built through a novel approach using software such as BGS Groundhog and Schlumberger Petrel/Eclipse 300. In the next steps, these tools will be utilized to investigate the thermal response and the relevant flow behaviour of the model, building upon reservoir engineering techniques. This requires simplification of the grid and consideration of relevant rock properties. The results will be analysed to quantify the uncertainty ranges for such a project and reduce the risk of planning expensive test boreholes. Model results correlated with temperature measurements and flow tests will be extremely valuable for evaluating the commerciality of this and future similar projects in Barnsley and elsewhere. It is critically important to help local authorities quantify the uncertainties in future smart energy systems to encourage development and implementation on the timescale urgently required to help with achieving the net-zero targets here and elsewhere in the UK.

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