Proceedings World Geothermal Congress 2023
Beijing, China, April 17 – 21, 2023

Lessons from mine water geothermal projects across Central Scotland

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Keywords: mine water, geothermal, thermal energy storage, Scotland

ABSTRACT

The University of Strathclyde (situated in the city of Glasgow, UK) has participated in several mine water geothermal projects across a range of budgetary scales from scoping studies (< £10,000 GBP) to major research projects (> £1 million GBP). This paper brings together the findings from these projects and summarizes important learning points for the delivery of mine water heating, cooling and thermal storage projects. In collaboration with industry, government bodies (such as data-holders and permitting organizations), landowners and local authorities, our team has experience with delivery of e.g., resource exploration, feasibility studies, site surveys, subsurface models, drilling, operational planning, and demonstration trials; all whilst maintaining conscientious dialogue with key stakeholders. Most of our efforts have focused on Central Scotland, which corresponds to the coal-rich geological region known as the Midland Valley. Like other mining regions across the world, local wealth was strongly linked to mining activity, and hence modern population and industrial centers are situated above legacy mine infrastructure. Responsible development of the substantial flooded subsurface void networks could allow mine water resources to host low-carbon heating, cooling and thermal energy storage solutions, helping to reduce energy CO_2 emissions and tackle endemic fuel poverty. Our cross-project pooled learnings indicate issues around non-systematic data recording and heterogeneity with respect to both site geology and infrastructure, but highlight potential solutions to address such uncertainties, such as better data integration, miner testimonies, and early matching of resource opportunities with surface energy end-uses.

1. INTRODUCTION

"It is unequivocal that human influence has warmed the atmosphere, ocean and land since pre-industrial times"

Eyring et al. (2021)

It is widely accepted that the burning of fossil fuels is the main driver of climate change (Chen et al., 2021). Global surface temperatures continue to increase at an unprecedented rate; temperatures in the period 2010-2019 were 0.8 - 1.3°C warmer than the pre-industrial 1850-1900 period (IPCC, 2021). Greenhouse Gases continue to be emitted at an unprecedented rate; in 2019 global greenhouse gas emissions were 54% higher relative to 1990 levels (IPCC, 2022). Over two thirds of global anthropogenic emissions result from energy generation and use (Ritchie et al., 2020), so it is imperative that we move beyond fossil fuels and embrace low-carbon energy resources.

In the United Kingdom (UK), heating represents almost 50% of total energy consumption and is responsible for a third of national CO_2 emissions (Crooks, 2018). The UK government has set a target of Net Zero greenhouse gas emissions by 2050 (UK Government 2021a; 2021b) and banned use of fossil-fuel heating systems in new build homes by 2025 (Committee on Climate Change, 2019). In Scotland, housing and environment are matters where decision making is devolved to the Scottish Government, which has set its own targets of Net Zero by 2045 (Scottish Government 2020) and no gas boilers in new homes by 2024 (Scottish Government 2022). Decarbonization of heating and cooling is far more challenging than transport or power due to decentralized generation and consumption, overreliance on fossil fuels and dependence on seasonal and weather conditions. Scotland failed to meet its 2020 target for 11% of all heat demand to be supplied from renewable sources, achieving only 6.4%, just over half of its ambitions, and illustrating the challenge in decarbonizing heating (Energy Saving Trust, 2021). With heating and cooling demands expected to rise in response to climate change, population increase and building demands (Mutschler et al., 2021), decarbonization of thermal energy will become even more critical if Net Zero commitments are to be met.

The thermal resource contained within disused flooded coal mines could potentially represent a valuable low carbon asset for heating, cooling and thermal energy storage. A quarter of UK homes and businesses are situated on former coalfields (Crooks, 2018), that host a highly permeable network of flooded mine workings which contain enormous volumes of groundwater (Banks et al. 2019) that can be exploited with heat pumps for heating and cooling applications or be used for storage of thermal energy. For brevity in this paper, we include heating, cooling and storage applications under the catch-all term of 'mine water thermal resources'.

The Coal Authority (TCA) is the executive non-departmental public body that owns, on behalf of the country, the majority of the coal in Britain, licenses coal mining, manages the effects of past coal mining, including subsidence damage claims, mine water pollution and other mining legacy issues. TCA has split the former UK coalfield regions into different hydraulic units known as mine water blocks (MWB). Individual MWB are designated based on information regarding hydrogeological linkages (e.g., interconnected mine workings) or barriers (e.g., faults or unworked coal), with each MWB being hydraulically distinct, i.e. mine water is contained within an MWB and is not in communication with other MWBs. Depending on the extent of operations and local geology, former mining regions can contain several MWBs; the Midland Valley of Scotland (MVS) hosts 12 MWB in total (Figure 1). The volume of the mine-worked area (i.e. from the base of the mine workings to land surface) in this region is c. 600 km^3 (Gillespie et al., 2013), with most extraction activities from the year c. 1800 following the introduction of steam power and mechanized mining techniques.

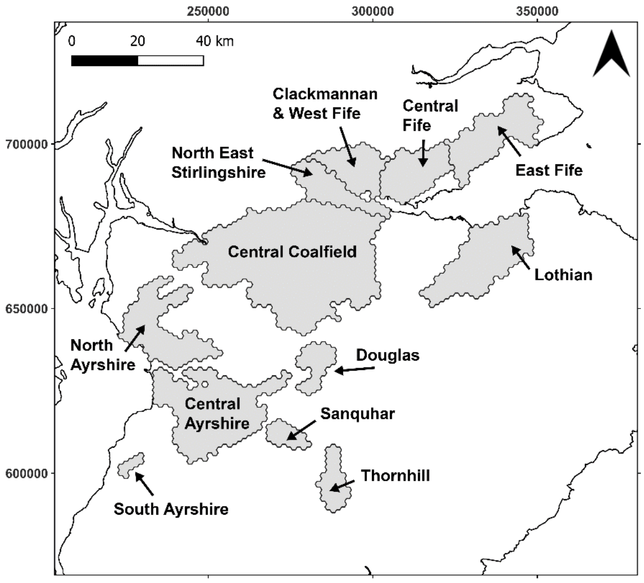

Figure 1: Mine water blocks within the Midland Valley of Scotland as managed by the Coal Authority (after Farr et al., 2021).

The impact of mine closures throughout the mid to late 1900s reverberates to the present day: former coalfield residents face a continuing legacy of poverty in comparison to non-coalfield areas. A third of ex-mining communities are situated within Scotland's most deprived 20% of neighborhoods and have proportionally more households in fuel poverty (Social Value Lab, 2020). Therefore, in addition to emission reduction benefits, mine water thermal resources provide a substantial socioeconomic opportunity.

However, there are challenges that must be overcome if mine water thermal resources are to be effectively integrated into future low-carbon energy systems. The following section highlights some of the key issues identified during completed and ongoing University of Strathclyde projects. Section 3 then details potential opportunities to de-risk development of mine water resources.

2. CHALLENGES

One of the first stages of any research project involves secondary data collection from existing sources. In the case of mine water thermal studies, these data largely pertain to the subsurface and its associated characteristics, e.g., geology, hydrogeology, mine geometries, and temperature. Availability and quality of data can vary across abandoned collieries, leading to uncertainty over the location of void spaces, geological conditions and the status of engineered infrastructure.

2.1 Data availability

Data availability is a critical part of research ethics in all fields as it allows large-scale analysis and reproducibility (Terdersoo et al., 2021). Currently, there is no single, comprehensive database where known UK subsurface data are publicly available (Jack et al. 2023). Therefore, the first challenge for prospect developers is identifying data holders. For the MVS, subsurface data exists and is often publicly available; some key sources include TCA, Scottish Environmental Protection Agency (SEPA), British Geological Survey (BGS), and the North Sea Transition Authority (NSTA). However, the quality and quantity of information and types of data held by these organizations can vary widely, e.g., TCA hold information about most of the mines in Scotland, but as much of the data is held behind a licensing barrier, it is not clear what information is available for a site of interest until an access request has been made. Depending on the nature of the data request, and the volume and type of information available, final provision of data can potentially take several weeks, extending initial timescales of projects. Furthermore, there is a limit as to how much mine data can be requested, meaning intended project scope may have to be re-scaled in accordance with the quantity of data available. Maintained records can be inconsistent across different mines, often because documentation during mining operations was focused on factors such as safety protocols and had no reason to consider future use of flooded mines for heating, cooling or thermal energy storage.

2.2 Gaps in available data

Mine abandonment plans are invaluable for characterizing mine workings, creating a digital subsurface mine model, and determining the available heat resource. They are vital for understanding the present-day state of the mine, including types of void space (e.g., shaft, roadway, pillar and stall working, collapsed long wall panels), engineered lining materials and support structures, and any abandonment measures such as constructed blockages and closure of ventilation doors between mine sections. Data availability has been a demonstrable issue for a research project assessing the feasibility of sensible mine shaft thermal energy storage (MSTES) at the former Comrie Colliery, Fife, situated in the Clackmannan and West Fife MWB (Figure 1). In this case, specific shaft and wider mine abandonment records are missing key details (Whittington et al. 2023). For example, it is uncertain if the target shaft was backfilled with waste material or what was used to cap the shaft during site decommissioning. Further ground investigation work is required to assess shaft cap composition and dimensions before any cap-penetrating drilling activities take place to assess the status of the shaft and potential for MSTES at this site. With increasing legacy mine data required for mine water thermal feasibility studies, such gaps in colliery records need to be addressed to reduce subsurface uncertainties for determination of available thermal resources and potential drilling investigations.

2.3 Correlation of mine seams

Recorded details and naming of coal seams can be inconsistent across coalfields, making it difficult to correlate worked seams of interest across collieries. Within the Clackmannan and West Fife MWB (Figure 1), mine workings date back several centuries, and seam records can be inconsistent (Walls et al. 2023a). For the area around the Dollar Colliery, the Coalsnaughton and Wallsend Seams have detailed accounts of coal extraction, the Alloa Splint and old portions of Coalsnaughton have outlines of old workings recorded without any internal detail, and the Alloa Rough seam is entirely unrecorded on mine plans. In the Central Ayrshire MWB (Figure 1), seam nomenclature is a challenge. The 36 Fathom coal seam overlies the Musselband coal seam, both established regional names; however, at the Barony Colliery, situated 2km west of the town of Auchinleck, the 36 Fathom seam was locally known as “Musselband” while the Musselband seam was known as “Bonanza”. While these details are usually well recorded in mine plans and logs, in this example, it would be easy to incorrectly correlate the 36 Fathom seam with the Musselband seam if sufficient care was not taken when analyzing mine plans and logs.

2.3 Spatial uncertainty

Where mine plans are available, issues can arise with spatial correlation of features that provided subsurface connections between different collieries or spanned multiple maps for a single set of workings. Mine abandonment plans were handwritten on paper or cloth after each seam in the mine was closed. This means that the more seams worked (and, in general, the older the mine), the more plans exist depicting the same area at various points in time. This has potential ramifications for the spatial accuracy of the subsurface mine infrastructure as it evolves and changes over the mine's lifetime, potentially leading to discrepancies in their mapped location. Arterial roadways were the primary mine roads, and they were built and supported to last the mine's lifetime (years to decades). As a result, they are more likely to remain structurally intact and provide effective hydrogeological connections between shafts and worked panels. As they are unlikely to have suffered from roof collapse, such roadways can be strongly considered for targeted drilling. However, for some collieries, it can be difficult to determine the continuity or position of roadways with certainty, either because their extent is only partially mapped or their location and geometry changes between neighboring plans. For example, the offset of the same feature across separate plans, often of different vintage, for the Barony Colliery was typically between 5 – 15m for roadways and 5 – 10m for worked panels.

2.5 Procurement of relevant geological samples

Most mine workings were excavated decades ago, when it was more difficult to capture detailed geochemical, mineralogical, and structural measurements. Comprehensive stratigraphic logs are available for many sites and may allow estimation of structural parameters. However, the logs do not usually provide sufficient detail to estimate the relevant geochemical parameters, such as iron, sulfur, and inorganic carbon content and speciation. Obtaining representative samples is thus desirable but can be easier said than done. Where mines penetrate dipping strata, representative lithologies may crop out at the surface, where they can be sampled, but thousands of years of surface weathering may alter the geochemistry compared to samples at depth. Active quarrying or recent opencast mining may allow for fresh samples to be collected. However, many opencast mine sites in the UK have undergone, or are in the process of mine reclamation, where the land is modified to an ecologically functional or economically useful state. This makes the outcropping lithologies inaccessible. It is advisable for companies or contractors undertaking reclamation works to collect type-samples of relevant lithologies and strata, to allow better characterization of now-inaccessible mine workings.

Figure 2: Mine water seep ochre precipitation being used as an educational opportunity at the Royal Society for Protection of Birds Lochwinnoch Nature Reserve, Renfrewshire (North Ayrshire MWB, Figure 1). Photo © Neil Burnside.

2.6 Climate change impacts on mine water resources

Mine water thermal resource developments must also be resilient to the effects of climate change, which include a cascade of projected impacts for water resources in Scotland (Adaptation Scotland 2021). To date, little work has been done to assess climate change impacts on mine waters, however changes in atmospheric temperature and the magnitude, frequency, and seasonality of rainfall could affect mine water level and resource temperature. Groundwater climate sensitivity could be examined using isotopes, water levels, and precipitation; allowing for assessment of recharge rates, recharge periods, and groundwater residence time. Physicochemical properties of water, such as pH and total dissolved solids, are affected by variations in carbon dioxide and temperature. Historic patterns of such commonly recorded parameters could give an indication of how water chemistry could be impacted by climate change. The concentration of iron in mine waters is a key issue for many locations; where mine water seeps, or breaks out, at the surface and comes into contact with atmosphere, dissolved iron is oxidized and precipitates out of solution as iron (oxy)hydroxides, such as ochre, which can foul surface waterways and cause environmental concerns (Figure 2). It is presently uncertain how mine water iron loads could be impacted by climate change, and so further research is required in this area.

3. OPPORTUNITIES

Our cross-project pooled learnings have also led to identification of opportunities to enhance our understanding of the subsurface flooded mine environment and address the challenges outlined above. These include lessons from the more widely advanced hot sedimentary aquifer industry, use and / or repurposing of boreholes and gravity discharges, enhancing site knowledge through the testimonies for former colliery workers, and use of isotope geochemistry to better understand mine system hydrogeology.

3.1 Lessons from hot sedimentary aquifer approaches

With only a handful of active mine water thermal projects across the globe (Walls et al. 2021), there is value to be gained from reviewing the approaches of parallel geothermal industries. Hot sedimentary aquifers (HSAs) have been exploited at similar temperature and depth profiles to mine water resources, though can also be found at greater depths (c. ≤5km) and provide higher temperatures (c. ≤100°C), making them feasible for heating and, albeit more rarely, power generation. Despite their huge low-carbon energy source potential, HSAs face similar issues to mine water resources with respect to subsurface uncertainty. However, with wider adoption and direct transference of learnings and relevant data from the hydrocarbon industry, efforts to de-risk development of HSA resources are more advanced. For example, Brémaud et al. (2023) have created an HSA database that captures a wide range of publicly available information for 45 HSA projects from across Europe. The Netherlands sets the standard in terms of data provision via a comprehensive free-to-access database that includes final borehole reports, well tests, and lithological logs. By comparison, HSA-relevant data for the UK is limited and largely confined to research articles or reports. If the Dutch standard for HSA information sharing and accessibility was to be replicated elsewhere, then additional and more detailed information on factors such as subsurface temperature and heat flow behavior could be used to improve understanding of mine water thermal resources.

3.2 Pre-existing surface resources

Subsurface uncertainty can be avoided in some locations by exploiting pre-existing mine water gravity discharges or pumped treatment schemes (Walls et al. 2022). These features have significant heating potential for circulation in district heating networks if harnessed by heat exchanger technology and converted to useable heat using a heat pump. The MVS hosts 4 pumped and 8 gravity discharge TCA mine water treatment sites, and at least 66 safely accessible presently untreated mine water gravity discharges with flow rates and temperatures of up to 117 l/s and 15°C (Figure 3). Using mine water which is present at the surface removes drilling capital expenditure and is less restricted by subsurface risks, however any heat consumers would have to be proximal to the discharge. When combined, MVS mine water treatment schemes and gravity discharges have been calculated to provide up to 48 MW of heat energy, enough to meet the peak heating demand of c. 12,000 two-bedroom homes (Walls et al., 2022).

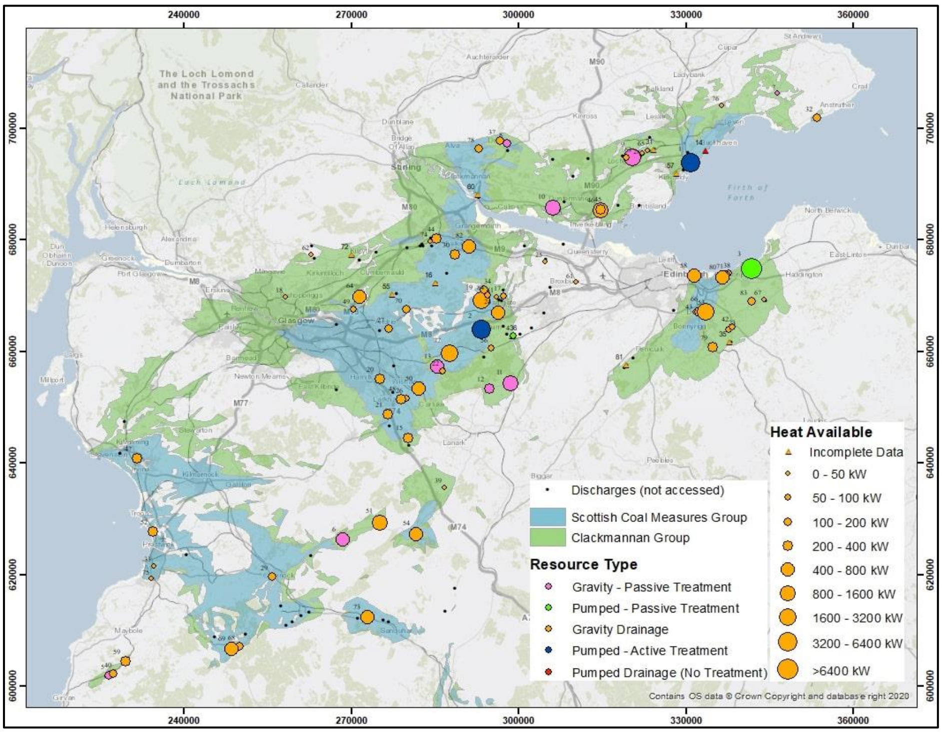

Figure 3: Location of TCA treatment schemes and untreated gravity discharges in the MVS. Contains British Geological Survey materials © UKRI 2022. Figure originally published by Walls et al. (2022).

3.3 Information from ex-miners

Interviews with former miners and colliery engineers can provide clarity and reduce uncertainty where there are gaps or ambiguities in historic colliery records. The value of such testimonies becomes even more significant for locations where scant information is available. Ex-miners can provide additional information about features recorded on mine plans such as mining techniques used, the extent of workings, roadway and panel geometries, and connectivity with neighboring collieries. They can also provide information on topics that are rarely documented within the mine plans, such as colliery abandonment measures, temperatures and nature of airflow during active mining, seams or areas that were more prone to water ingress, and observations of initial mine flooding following deactivation of dewatering pumps. Due to the varying state of available information for sites of interest to University of Strathclyde projects across the mine water blocks of the MVS, interviews were carried out with a number of ex-miners with decades of experience working across a number of collieries. These efforts have allowed us to address sometimes significant gaps in technical knowledge of collieries under investigation for potential mine water thermal developments. In combination with available mine plans and records, the extra information supplied by ex-miners will reduce risk related to site exploration activities, inform conceptual site models, and enable more robust parameterization of numerical modelling studies.

3.4 Combining ground investigation with mine water resource assessment

Ground stability investigative (GSI) drilling is required for building projects above suspected shallow mine workings. Added resource assessment value can be gained from conversion of GSI boreholes into mine water reservoir monitoring wells. This upgrade would require addition of liners, screens and standpipes as a minimum, and may require extension of the borehole into deeper, more desirable flooded void spaces. This would require additional time and financial resources for GSI borehole conversion, meaning greater budgetary requirement than stand-alone GSI work, but may prove more economically efficient than separate GSI and mine water exploration drilling campaigns by avoiding costs associated with additional boreholes and rig mobilization. Using generic indicative costs for an array of twenty GSI wells, Walls et al. (2023a) estimate that the upgrade (at the time of drilling) of three boreholes to mine water assessment wells would add an additional 14% to the cost of a stand-alone GSI drilling job. Upgraded and lined boreholes may prove too narrow diameter to perform comprehensive mine water pump tests but would allow for falling head tests to measure transmissivity and response of the mine water reservoir. They also enable determination of water level, temperature and hydrochemistry (Figure 4), providing key information for successful development of any mine water thermal resource (Burnside et al. 2016a). For example, chemical analyses deliver valuable insights into scaling and corrosion risks, which are an important consideration for engineering design of mine water thermal energy systems.

Figure 4: Members of the co-author team, and colleague Mike Schiltz, sampling a mine water monitoring borehole in Dollar, Clackmannanshire (Clackmannan and West Fife MWB, Figure 1). Photo © David Walls.

3.5 Advanced resource characterization with stable isotopes

Stable isotopes of $\delta^{18}O$, $\delta^{2}H$, and dissolved sulfate $\delta^{34}S$ in mine waters can be used to provide more detailed information on water sources, solutes origins, and water-rock-interaction histories (Banks et al. 2020; Burnside et al. 2016b). Recent analyses and interpretation of these isotopic ratios from the UK Geoenergy Observatories (UKGEOS) Glasgow Geothermal Energy Research Field Site (GGERFS), situated in the Central Coalfield MWB (Figure 1), is delivering new insights into isotopic distribution within mine water systems (Walls et al. 2023b). GGERFS hosts a borehole array which penetrates a shallow (<100 m) series of overlapping coal mine workings and proximal drift and hard rock geology (Monaghan et al. 2022). As has commonly been found across Europe (e.g., Janson et al. 2016; Loredo et al. 2017), $\delta^{18}O_{H2O}$ and $\delta^{2}H_{H2O}$ values indicate a recent meteoric origin for GGERFS mine waters (Figure 5). Sulfate $\delta^{34}S$ values for mine waters sampled during pump tests ($\overline{x}$ = +20.3‰), show a clear departure from putative $\delta^{34}S$ parent coal seam pyrites ($\overline{x}$ = +5.0‰) and from groundwaters in non-coal bearing sediments ($\overline{x}$ = +0.3‰). Whilst the origin of mine water $\delta^{34}S_{SO4}$ remains unclear, it is unlikely due to simple pyrite oxidation, and $\delta^{34}S_{SO4}$ contributions from one or more processes such as evaporite dissolution, fractionation via sulfate reducing bacteria, and historic mixing with saline formation waters of marine or evaporitic origins (Banks et al. 2020) are probable. Regardless of source, mapping of $\delta^{34}S$ in mine water systems can serve to map out zones of hydraulic connectivity (i.e., common wide-spread bulk value) or compartmentalization (i.e., distinct areas with divergent values), and help address spatial uncertainties such as continuity of roadways and the collapse-state of workings.

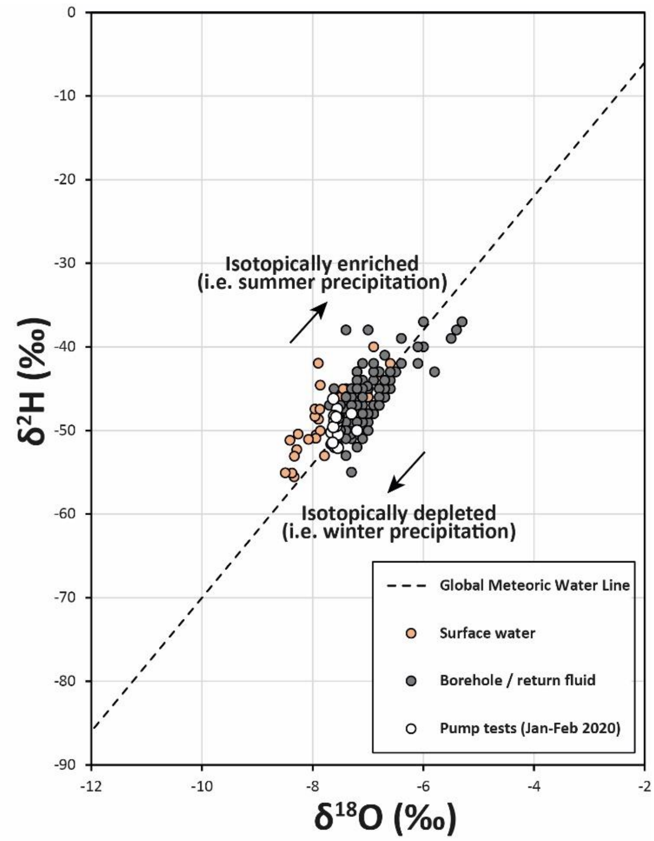

Figure 5: GGERFS $^{\delta 18}O_{H2O}$ and $^{\delta 2}H_{H2O}$ results. Plotted groups include surface waters (n = 41), borehole / return fluid during drilling operations (n = 114), and pump test samples (n = 15). Data redrawn from (Monaghan et al., 2022).

4. DISCUSSION AND CONCLUSION

We have provided a summary of some common challenges encountered across mine water projects that the University of Strathclyde have been involved in and reported promising opportunities which could go some way to addressing these issues. These have ramifications for practical realization of mine water thermal energy developments.

Firstly, it is important to view mine water thermal resources through a "system of systems" framing. Whilst there are distinct systems at play (e.g., subsurface hydrogeology or surface engineering) that require different specialist skills and thus independent assessment, these cannot be examined in isolation. For example, if one studies and parameterizes the geology in isolation of topside constraints, such as demand profiles, planning constraints or logistics, one might miss crucial constraints on the subsurface assessment. Without this information, what looks like the 'best' option for subsurface development may in fact be impossible due to surface constraints. Thus, it is crucial at very early stages of project planning, to integrate subsurface knowledge with surface plans. There may well be trade-offs between surface and subsurface constraints on optimal well or energy center locations as we have experienced in a number of projects.

Secondly, the established mine water paradigm of exploiting roadways over workings may not be so straightforward. Uncertainty in data derived from mine plans, particularly in deeper mines, can lead to roadway location errors in excess of achievable drilling accuracy. Even if mine plans are accurate, tender specifications often require verticality of borehole drilling within 1:300; i.e., for a 300m deep target, the base of the well must be within 1 meter of the surface initiation point of drilling in x-y space; this is equivalent to a deviation of just 0.2° from vertical. For a target at 600m depth, as at some mines we have assessed in Scotland, a 2m horizontal error in verticality drastically reduces the chances of successfully hitting a c. 3 to 6m wide roadway target. Others have suggested verticality of wells can be as much as 1 degree out, which at 600m equates to a horizontal error of 10.5m. Thus, we find that for deeper mines, even with the uncertainty in goaf permeability, targeting collapsed workings (10s to 100s m wide) may be a less risky approach than targeting roadways.

Accurate site characterization is essential, but as we have seen, there is an inconsistent level of information available for UK collieries. Lack of a comprehensive open-access UK subsurface database, data gaps in mine plans, lack of consistency in recording features across neighboring plans, and the inaccessibility of the mines can make it challenging to tackle subsurface uncertainty for mine water thermal systems. Spatial data on mine plans, such as location, geometry and interconnection of roadways and worked seams, are subject to uncertainty and subjectivity, which could have implications for resource estimation and optimization of drilling locations. In addition, if mine water thermal resources are to provide a sustainable source of low-carbon heat, they will also need to be resilient to the effects of climate change, which are projected to include a cascade of temperature and rainfall impacts on water resources in Scotland.

The opportunities detailed in this paper may provide tangible solutions to such challenges. The mine water thermal industry could be enhanced by improving data accessibility and sharing, such as the example set by the Netherlands' open-access subsurface database. Depending on proximity to mine water gravity discharges or treatment works, landowners and new-build developers could avoid subsurface uncertainties and drilling costs by utilizing these potentially high heat yield surface features. Data gaps and ambiguities on mine plans can be addressed by gaining knowledge from local ex-miners. The testimonies of former colliery workers are mostly relevant to relatively recent mines and could help to de-risk exploration activities and inform predictive modelling studies. All building projects require ground investigation boreholes; in locations overlying flooded mines these could be extended and upgraded to resource assessment boreholes for the fraction of the cost of a completely separate mine water exploration drilling campaign. Finally, advances in knowledge of mine system isotopic distributions, particularly $\delta^{34}S$, are providing new insights into mine water resource behaviors.

We hope that the lessons detailed in this paper can help contribute to socially and environmentally responsible development of low-carbon mine water thermal resources in Scotland and around the world.

ACKNOWLEDGEMENTS

This research was supported by EPSRC award EP/W027763/1, NERC NEIF award 2301.0920, and Energy Technology Partnership Scotland awards PR007-HE, PR043-HE and PR051-HE. IO was supported by the BEIS Biomass Feedstocks Innovation Programme: Phase 1. SFJ is funded by the Data Lab and COWIFonden. DW and CG are funded by the GeoNetZero Centre for Doctoral Training in Geoscience and the Low Carbon Energy Transition (funded by NeoEnergy Upstream). For the purpose of Open Access, the author has applied a Creative Commons Attribution (CC BY) to any Author Accepted Manuscript (AAM) version arising from this submission. The authors would like to acknowledge all the colleagues and collaborators who have contributed to our various mine water projects.

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