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

Monitoring and Modelling Mine Water Geothermal at the UK Geoenergy Observatory in Glasgow, UK

Monaghan A.[1], Kuras O.[2], Boon D.[2], Abesser C.[3], Starcher V.[1], MacAllister D.J.[1], Spence M.[2], Gonzalez Quiros A.[1], Walker-Verkuil K.[1,] Wilkinson P.[2]

British Geological Survey, Edinburgh[1], Keyworth[2] and Wallingford[3], UK.

als@bgs.ac.uk

Keywords: mine water geothermal, geo-observatories, monitoring, conceptual hydrogeological model

ABSTRACT

The British Geological Survey (BGS) has constructed the UK Geoenergy Observatory in Glasgow and operates this at-scale underground science laboratory on behalf of the Natural Environment Research Council and UK Research and Innovation. As one of the two new UK Geoenergy Observatories, the Glasgow Observatory facilitates collaborative research to improve understanding of subsurface processes, environmental and induced change related to mine water energy. It provides scientific and engineering infrastructure for investigating the shallow, low-enthalpy geothermal energy and thermal storage resources available in abandoned and flooded coal mine workings. Such resources could provide low-carbon renewable heating and cooling for community-scale district heating networks and other heat demands. The Glasgow infrastructure is not connected to a heat user, so it is flexible for research and development. The facility includes two abstraction and two injection mine water boreholes spaced 10-190 m apart, equipped with variable speed submersible well pumps optimised for up to 12 litres/second; a heat centre with three types of heat exchanger; a 200kW output heat pump/chiller for active heating or cooling of mine water in a sealed open loop; a sensor logging system; 8 additional boreholes and extensive environmental monitoring equipment.

Borehole monitoring capability includes hybrid fibre-optic distributed temperature sensing (DTS) cables behind casing for passive monitoring or for performing heat pulse tests in active mode, as well as sensors for measuring geoelectrical properties. The latter use arrays of permanently installed downhole electrodes to measure subsurface electrical resistivity within the top ~90 m, enabling both in-hole and cross-hole tomography (ERT) for tracking subsurface changes in 4D. Collecting high-quality subsurface DTS monitoring data allows detection of small changes (±0.01°C) in temperature every 0.25 m along the fibre, within the mine water aquifer and rock mass as part of ongoing baseline change monitoring, as well as thermal pulses during and after heat injection and extraction experiments. Together with pressure data from downhole hydrogeological data loggers, and flow and monitoring of heat pump/chiller performance, this provides an at-scale field facility for evaluating the engineering and energy performance of the various components of mine water geothermal systems. The evidence collected at the facility will improve understanding of environmental sustainability, materials and component performance, informing design and regulation, and supporting public engagement in geothermal energy.

An initial hydrogeological and hydrochemical conceptual model developed using borehole, pump test and baseline monitoring data has been used to interpret results from the system construction phase. Integrated analysis of hydrogeological, geoelectrical, thermal and geochemical data is shown to provide a much more comprehensive understanding of geothermal processes in low temperature mine water systems. Insights gained from research undertaken during commissioning will enable visiting researchers to fine-tune their proposals for research and innovation at the Glasgow Observatory.

1. INTRODUCTION

Net Zero emissions targets in the UK by 2050 or earlier require decarbonisation of the 90% of home heating from fossil fuel sources (HM Government 2020). Low enthalpy, shallow geothermal heat recovery from, and thermal storage in, abandoned coal mines offers a significant opportunity beneath many towns and cities in the UK. The mines have become naturally flooded with warm groundwater upon closure and with the cessation of dewatering. The man-made workings and rock mass surrounding them have a higher permeability compared to unmined rock due to still-open and partially collapsed mined voids and collapse-related fractures forming an 'anthropogenically-enhanced aquifer'. This warm mine water can be abstracted through a borehole and passed through a heat pump, via a heat exchanger, to provide space heating for homes and businesses, before being returned within a sealed loop to a different part of the mine system via a second re-injection borehole (more detail in Banks et al. 2017). Flooded mine workings can act as a thermal reservoir, with the potential to provide both heat recovery and heat storage for community-scale district heating networks.

Small numbers of successfully operating mine water geothermal and heat storage schemes have proved the concept of mine water geothermal for space heating and cooling (Verhoeven et al 2014; Loredo et al 2016; Walls et al. 2021). The large resource potential in the UK (Bailey et al 2016; Farr et al 2016, Gluyas et al 2019) has yet to be widely exploited. Increasing numbers of commercial demonstration projects (e.g. Banks et al. 2022; Coal Authority accessed 2022) are complemented by the UK Geoenergy Observatory in Glasgow (Monaghan et al. 2021, 2022). This is an at-scale infrastructure designed for research and innovation to improve understanding of subsurface processes, environmental and induced change, and provide an open evidence base.

1.1 UK Geoenergy Observatory for mine water geothermal

Between 2018-2022, BGS has constructed the UK Geoenergy Observatory in Glasgow, operated on behalf of the Natural Environment Research Council and UK Research and Innovation. The facility includes four mine water boreholes in a sealed open loop currently configured as two abstraction and two injection boreholes. The boreholes are spaced between 10 and 190 m apart, two

are screened at a mine working at approximately 45 m below ground and two at approximately 85 m (see Monaghan et al. 2021). Abstraction boreholes are equipped with variable speed submersible well pumps optimised for flow rates between 3 and 12 litres/second. The mine water pipe is connected to a heat centre with three types of heat exchanger, a 200 kW output heat pump/chiller for active heating or cooling of mine water and a sensor logging system. The infrastructure is not connected to a heat user, so it is flexible and accessible for research and development. There are 8 additional boreholes plus above and below ground environmental monitoring equipment to measure soil/ground gas, ground motion (InSAR) and weather conditions.

This paper describes some of the borehole monitoring capability at the Observatory, preliminary integration into a conceptual hydrogeological model and a numerical heat and flow model which provides insights into baseline and geothermal processes in low temperature mine water systems.

2. BOREHOLE TEMPERATURE MONITORING

Five boreholes screened at mine workings and a sixth sensor testing borehole were installed with hybrid fibre-optic distributed temperature sensing (DTS, e.g. installation details in Barron et al. 2020) cables for measuring thermal change and performing heat pulse tests. Collecting high-quality subsurface DTS monitoring data allows detection of small changes (±0.01°C) in temperature every 0.25 m along the cable frequently (e.g. every 30 minutes) within the mine water aquifer and coupled rock mass. This may be as part of ongoing environmental monitoring, during and after heat injection and extraction experiments, or in response to active mode heating of the copper-cored fibre-optic heated cable.

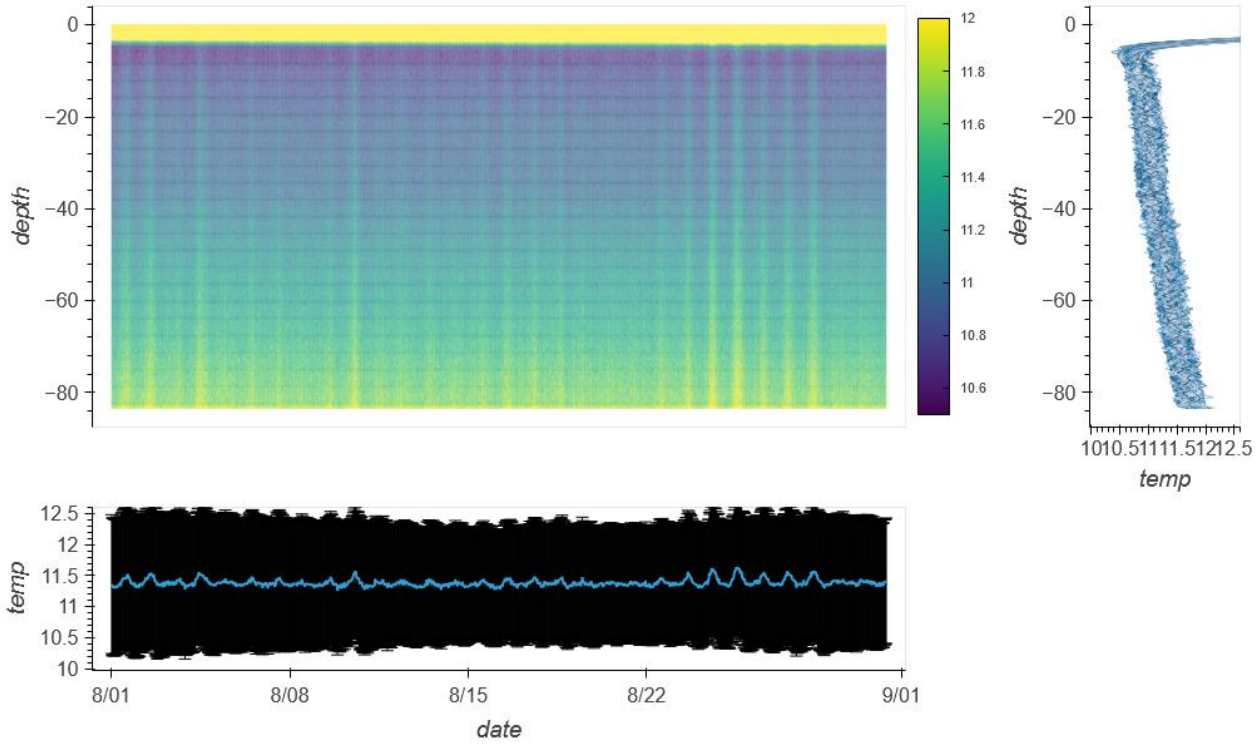


Figure 1 Continuous fibre-optic DTS measurements from borehole GGA08 in August 2021; 30 minutes frequency time-temp-depth plot on left, stacked temperature-depth plot for a 1 month of measurement on the right BGS©UKRI

A set of data from one month is given as an example (August 2021; Figure 1). This data characterises the undisturbed ground temperature profile in the upper 80m. The image in the profile (Figure 1, top left) shows a month of continuous data collected at 30-minute intervals. Between 0-8 m below ground surface, is within the 'zone of seasonal fluctuation', where in August the temperature is relatively warm (yellow colour indicates >12°C). Below 8 m, the ground temperature increases linearly with depth, in this case reaching 11.8°C at around 82 m below ground (GGA08). Below around 38m, the depth of the base of the superficial deposits, there is a notable increase in the shallow geothermal gradient. This may be related to the base of the urban heat island effect and/or a change in the hydrogeological regime, as described later in the conceptual model section of this paper. The daily vertical 'yellow stripes' on parts of Figure 1 top and bottom trace showing, means (blue) and standard deviations, are likely to be an artefact caused by the DTS interrogator electronics being affected during hot days as these events correlate well with days when DTS cabinet air temperature exceeded 30°C. Work is ongoing for further calibration, benchmarking, and correction of DTS data to compensate for these surface temperature effects, along with future testing of the active mode DTS system and continuous monitoring during heat pump/chiller commissioning.

Further measurements over longer periods are needed to establish representative temperature ranges and elucidate the controlling factors on local temperature gradient, such as the urban heat island (UHI). However, this initial dataset highlights how the DTS capability will be an invaluable tool for measuring subtle temperature changes at high spatial and temporal resolutions, such as when researchers start controlled field experiments with the heat injection and extraction infrastructure.

Time-series groundwater temperature, water level and conductivity data are also being measured by downhole hydrogeological data loggers in the boreholes. This generally shows stable temperatures around 11-12°C with some seasonal variability changes. During

test pumping, Shorter et al. (2021) documented changes of up to c. 0.4°C within the pumping borehole over timescales of seconds-minutes. During these initial pumping tests there were pressure responses logged between the Glasgow Upper and Main mine workings, but not temperature responses.

3. BOREHOLE GEOELECTRICAL MONITORING

In 2019, three BGS PRIME electrical resistivity tomography (ERT) systems (Holmes et al. 2020) were deployed on three neighbouring borehole clusters, along with the fibre-optic cables. They use arrays of permanently installed downhole electrodes to measure subsurface electrical resistivity within the top ~90 m, enabling both in-hole and cross-hole tomography (ERT) for tracking thermal and mine water property variations in the shallow subsurface induced by active experimentation. ERT measurement sequences have been developed to help maximise sensitivity and the information that can be derived from geoelectrical imaging.

Figure 2 shows baseline ERT images between the three pairs of boreholes. Due to the significant difference in borehole depth and hence ERT array length, the ERT measurements are not symmetrical across each cross-hole panel, and care must be taken when placing constraints on the ERT inversion. Layers of higher resistivity (orange-red colours) correspond closely with sandstone intervals in the borehole geological log interpretations, and lower resistivities (green-yellow) with mudstone. The lowest resistivity layers appear to correspond to packed waste and coal seams.

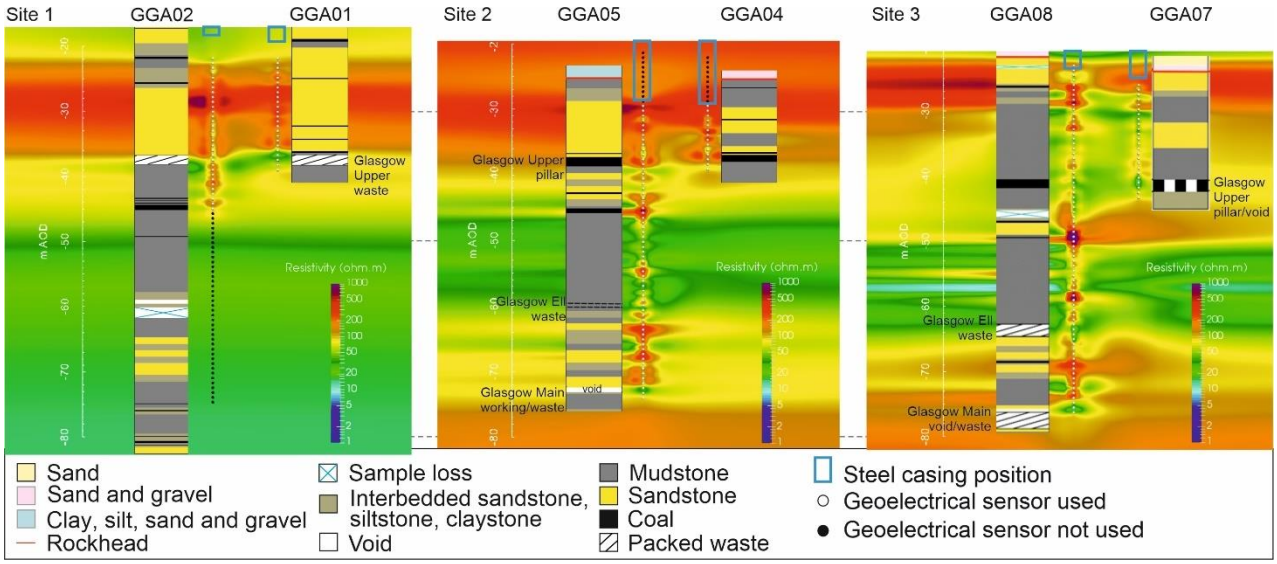


Figure 2 The baseline response in the three cross-borehole pairs installed across three levels of mine working. BGS©UKRI

Since groundwater conductivity changes with temperature by ~2%/°C, changes in the resistivity images are expected to help map spatial and temporal thermal and water chemistry changes in the rock mass during future, controlled field experiments.

4. INITIAL CONCEPTUAL HYDROGEOLOGICAL MODEL

An initial hydrogeological and hydrochemical conceptual model developed using borehole, pump test and baseline monitoring data has been used to interpret results from the system construction phase (Figure 3; Monaghan et al. 2022). This understanding is critical for geothermal activities that involve abstraction and re-injection of groundwater. In the initial conceptual model the groundwater flow system is dominated by the abandoned, flooded mine workings. Both aquifer testing and the water chemistry analysis indicate that in its 'baseline' state, flow is predominately laterally through individual mine workings; likely a combination of flow through voids and waste in the workings, and fractures in the surrounding rock (Shorter et al. 2021, Palumbo-Roe et al., 2021; Bearcock et al. 2022, Monaghan et al. 2022). Test pumping proved that individual mine water boreholes can yield high flows of greater than 20 litres/second with groundwater temperatures in the mine workings of 11.5-12.5 °C. There is evidence that separate mine workings have limited connectivity. Pumping in one mine working was shown to induce small changes in groundwater levels in monitoring boreholes screened across a different mine working. Sandstone immediately above the Glasgow Upper mine workings is strongly connected to those workings. The properties of the sandstone aquifer and strength of connectivity with the Glasgow Upper mine workings is interpreted to be modified by fractures induced by mining activity. The five-hour pumping tests conducted do not provide evidence for groundwater in the shallow superficial deposits, above the Paisley Clay Member, being directly connected to the bedrock aquifer, though this may be a consequence of the pumping rate and test duration. Groundwater levels in the Glasgow Main are higher than those in the Glasgow Upper mine working, indicating that groundwater flow is upwards. The initial conceptual model (Figure 3) indicates that this site is typical of many shallow mine workings in Scotland, and flow rates from initial test pumping and borehole spacings are representative of those of a small scale mine water heat scheme, when compared to larger schemes at Heerlen, Netherlands (Verhoeven et al. 2014) or Gateshead, UK (Steven 2021). As such, the site can be regarded as representative to undertake further mine water geothermal research. The conceptual model will be iterated and further refined once temperature, geoelectrical and hydrogeological monitoring data from commissioning and field experiments becomes available.

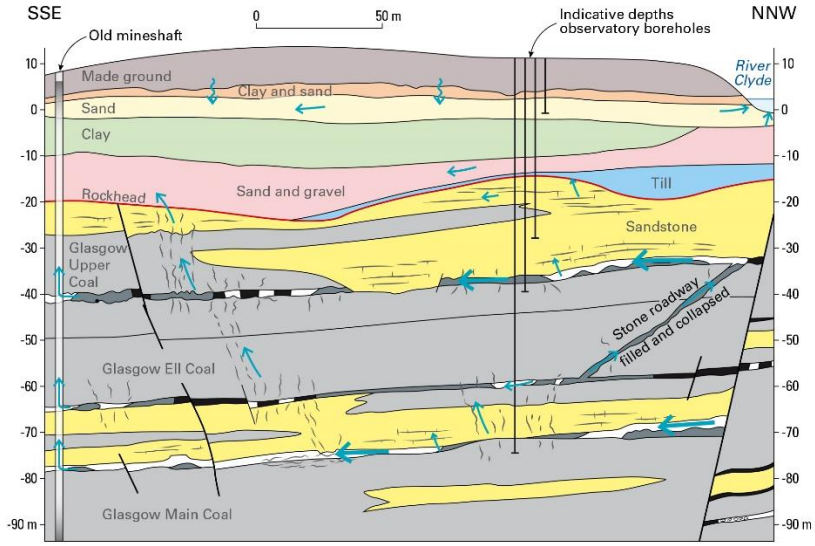


Figure 3 Summary conceptual model of mined Coal Measures in the vicinity of the UK Geoenergy Observatory in Glasgow with representative features shown. Blue arrows indicate groundwater flow. Depths are metres relative to Ordnance Datum (mean sea level). Mine workings are water filled, grey within mine workings is mining waste, black is intact coal from Monaghan et al. (2022) BGS©UKRI

5. INITIAL NUMERICAL HEAT AND FLOW MODELLING

Groundwater flow and heat transport finite element modelling, using FEFLOW and COMSOL Multiphysics, is being implemented at regional and local scales to obtain estimates of the spatial and temporal distribution of piezometric heads, water flow directions and temperatures changes in and around the Observatory. At the regional scale, the initial hydrogeological conceptual model and geological analysis were used to identify the main hydrogeological units and to define the model boundaries of the system using structural and stratigraphic information. At the local scale, mine working plans were digitised, analysed to define hydrogeological domains, and geometrically debugged before transferring the information to the modelling software. Discrete elements that represent key mine features (i.e. main roadways, voids in stoop and room zones) are used for meshing and computational efficiency. Preliminary results provide initial estimates of flow directions, temperature distribution and response times of the system under use of the geothermal infrastructure, including open-loop abstraction and re-injection configurations (Figure 4), and for planning and scheduling of field tests, system recovery times, and monitoring activities. In the future, models will be calibrated with the responses measured from monitoring and geothermal research.

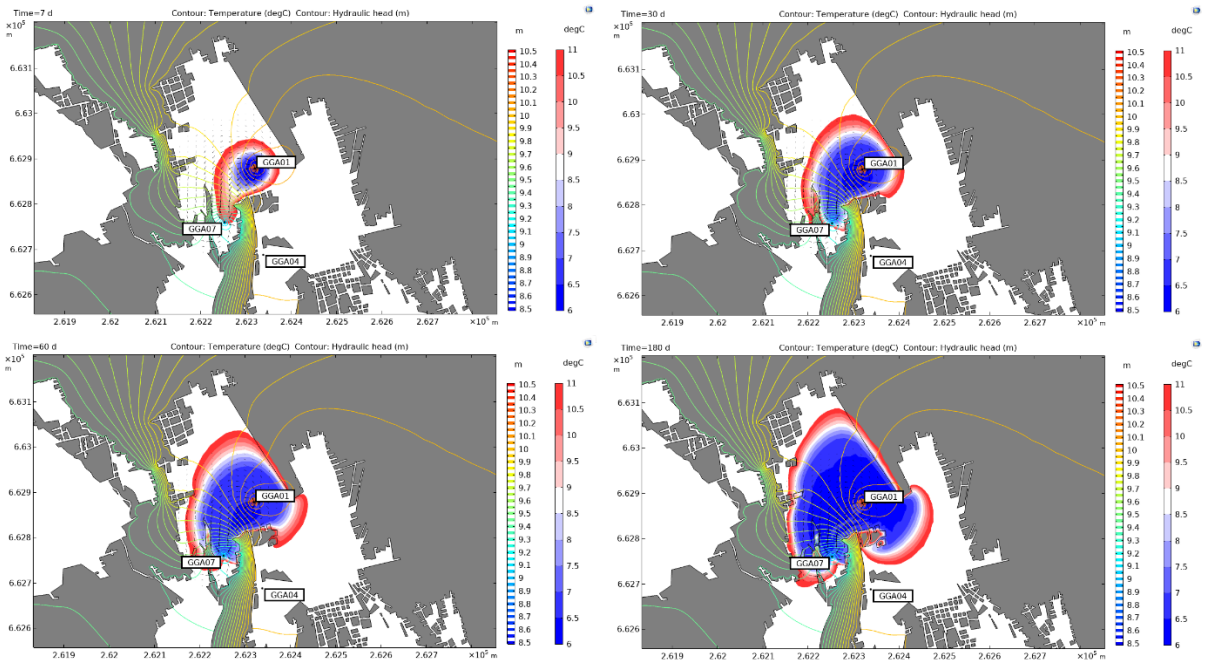


Figure 4 Preliminary results of numerical modelling of abstraction (GGA07) and re-injection at 6.5 °C (GGA01) in the Glasgow Upper with rates of 12 litres/second. ΔT=5°C for mine water temperature of 11.5 °C. Line contours show hydraulic heads and filled contours temperature distributions after 7, 30, 60 and 180 days. White areas are coal mine workings recorded on mine plans. Grey areas are non-worked coal seams or sandstone at the same stratigraphic level. BGS©UKRI

6. CONCLUSION

Hydrogeological, geoelectrical, thermal and geochemical monitoring data from an at-scale research infrastructure, the UK Geoenergy Observatory in Glasgow, Scotland, has started to reveal the complex geological and anthropogenic variability in the subsurface properties and hydrogeology in abandoned, flooded mine workings. Mine water geothermal is viewed as a promising solution for renewable heating, cooling and thermal storage in the UK, at a variety of scales from municipal buildings to district heat networks, and this level of monitoring offers unprecedented insights into the baseline and dynamic behaviour of these shallow geothermal systems.

Future integrated analysis and research using these monitoring and modelling technologies will realise a more comprehensive understanding of geothermal processes in low temperature mine water systems. The evidence collected at the facility will improve understanding of system responses and environmental sustainability, informing regulation, and supporting public engagement in geothermal energy. Further monitoring of heat/flow under operation of the geothermal system and heat pump/chiller performance will also inform the engineering design and energy performance of the various components. Insights shared here will enable visiting researchers to fine-tune their proposals for research and innovation at the Glasgow Observatory (see www.ukgeos.ac.uk for more details on how to access the UK Geoenergy Observatories).

ACKNOWLEDGEMENTS

This work was supported by the British Geological Survey via NERC national capability funding.

REFERENCES

Bailey, M.T., Gandy, C.J., Watson, I.A., Wyatt, L.M. and Jarvis, A.P. Heat recovery potential of mine water treatment systems in Great Britain. *International Journal of Coal Geology*, **164**, (2016), 77-84, https://doi.org/10.1016/j.coal.2016.03.007

Banks, D., Athresh, A., Al Habaibeh, A. and Burnside, N. Water from abandoned mines as a heat source: practical experiences of open and closed-loop strategies, United Kingdom. *Sustainable Water Resources Management*, **5**, (2017) 29-50, https://doi.org/10.1007/s40899-017-0094-7

Banks, D., Steven, J., Black, A. and Naismith, J. Conceptual Modelling of Two Large-Scale Mine Water Geothermal Energy Schemes: Felling, Gateshead, UK. *Int. J. Environ. Res. Public Health*, **19**, (2022), 1643. https://doi.org/10.3390/ijerph19031643

Barron, H.F., Starcher, V., Monaghan, A.A., Shorter, K.M. and Walker-Verkuil, K. Mine water characterisation and monitoring borehole GGA05, UK Geoenergy Observatory, Glasgow. *British Geological Survey Open Report*, OR/20/025, (2020) 35pp. http://nora.nerc.ac.uk/id/eprint/528052/

Bearcock, J.M., Walker-Verkuil, K., Mulcahy, A., Palumbo-Roe, B., MacAllister, D.J., Gooddy, D.C., and Darling, W.G. UK Geoenergy Observatories : Glasgow baseline groundwater and surface water chemistry dataset release September 2020 - May 2021. *British Geological Survey Open Report*, (2022), 151pp. https://nora.nerc.ac.uk/id/eprint/532731/

Coal Authority. Geothermal energy from abandoned coal mines. (Accessed September 2022) https://www2.groundstability.com/geothermal-energy-from-abandoned-coal-mines/

Farr. G., Busby, J., Wyatt, L., Crooks, J., Schofield, D. I. and Holden, A. The temperature of Britain's coalfields. *Quarterly Journal of Engineering Geology and Hydrogeology*, **109**, (2020) https://doi.org/10.1144/qjegh2020-109

Gluyas J. G., Adams C. A., and Wilson I. A. G. The theoretical potential for large-scale underground thermal energy storage (UTES) within the UK. *Energy Reports*, **6**, (2020) 229-237. https://doi.org/10.1016/j.egyr.2020.12.006

HM Government 2020. Powering our Net Zero Future, Energy White Paper, CP 337. ISBN 978-1-5286-2219-6 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/945899/201216_BEIS_EWP_Command_Paper_Accessible.pdf

Holmes, J., Chambers, J. E., Meldrum, P. I., Wilkinson, P. B., Boyd, J., Williamson, P., Huntley, D., Sattler, K., Elwood, D., Sivakumar, V., Reeves, H., and Donohue, S. Four-dimensional electrical resistivity tomography for continuous, near-real-time monitoring of a landslide affecting transport infrastructure in British Columbia, Canada. *Near Surface Geophysics*, **18**, (2020) 337-351. https://doi.org/10.1002/nsg.12102

Loredo, C., Ordóñez, A., Garcia-Ordiales, E., Álvarez, R., Roqueñi, N., Cienfuegos, P., Peña, A. and Burnside, N. M. Hydrochemical characterization of a mine water geothermal energy resource in NW Spain. *Science of the Total Environment*, **576**, (2017), 59-69. doi:10.1016/j.scitotenv.2016.10.084

Monaghan, A.A., Starcher, V., Barron, H.F., Shorter, K., Walker-Verkuil, K., Elsome, J. et al. Drilling into mines for heat: geological synthesis of the UK Geoenergy Observatory in Glasgow and implications for mine water heat resources. *Quarterly Journal of Engineering Geology and Hydrogeology* (2021). https://doi.org/10.1144/qjegh2021-033

Monaghan A.A. and 25 others. Time zero for Net Zero: a coal mine baseline for decarbonising heat. *Earth Science, Systems and Society*, (2022) https://doi.org/10.3389/esss.2022.10054

Palumbo-Roe, B., Shorter, K. M., Fordyce, F. M., Walker-Verkuil, K., Ó Dochartaigh, B.E., Gooddy, D. C. and Darling, W. G. UK Geoenergy Observatories: Glasgow Borehole Test Pumping - Groundwater Chemistry. *British Geological Survey Open Report*, OR/21/030. (2021) 73pp. http://nora.nerc.ac.uk/id/eprint/531098/

Shorter, K., O Dochartaigh, B.E., Butcher, A., MacDonald, A., Elsome, K. and Burke, S. Data release and initial interpretation of test pumping of boreholes at the Glasgow UK Geoenergy Observatory. *British Geological Survey Open Report*, OR/21/016 (2021) http://nora.nerc.ac.uk/id/eprint/530507/

Steven, J. (2021). From Venture Pit to Walker Shore, coal and heat and fathoms of core': Mine water Heat Exploitation in Newcastle/Gateshead. Presentation accessed August 2021 at IEA Geothermal | 2021 Mine Water Geothermal Energy Symposium - International Energy Agency geothermal (iea-gia.org)

Verhoeven, R., Willems, E., Harcouët-Menou, V., De Boever, E., Hiddes, L., Op'T Veld, P. and Demollin, E. Minewater 2.0 project in Heerlen the Netherlands: transformation of a geothermal mine water pilot project into a full scale hybrid sustainable energy infrastructure for heating and cooling. *Energy Procedia*, **46**, (2014), 58-67, https://doi.org/10.1016/j.egypro.2014.01.158

Walls, D.B., Banks, D., Boyce, A.J. and Burnside, N.M. (2021) A review of the performance of minewater heating and cooling systems. Energies, 14, 6215. https://doi.org/10.3390/en14196215