Decarbonising heat via the subsurface

The UK is poised to scale up use of geothermal energy. Alison Monaghan and Mike Spence discuss new facilities to investigate and quantify our shallow geothermal resources using the UK Geoenergy Observatories

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4 September 2023

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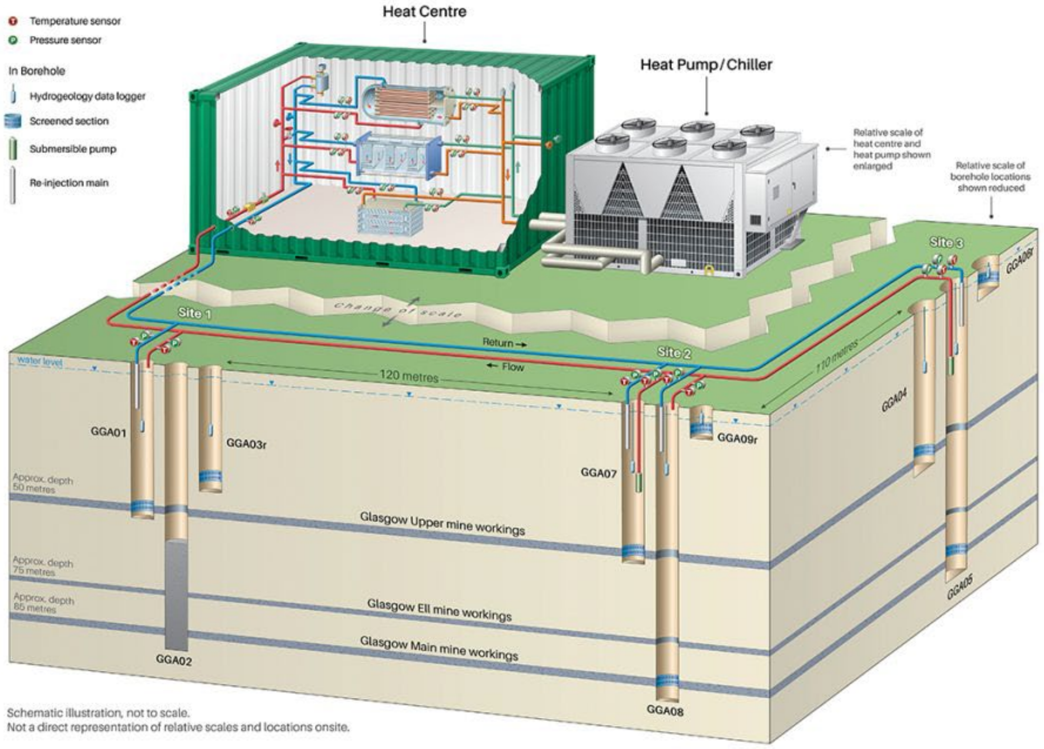

Figure 1: 3D schematic of the Glasgow Observatory boreholes and geothermal infrastructure to abstract or store heat at scale in a number of flexible combinations. Not all sensors and valves are shown. Geology is simplified. BGS © UKRI 2023.

Adverts on TV now promote heat pumps for home heating. This tangible change follows numerous Government strategies and policies that include decarbonising heat to help achieve net-zero carbon-emissions targets. The strategies include ambitious growth targets, such as the installation of 600,000 heat pumps (air and ground source) per year by 2028 (HM Government Energy White Paper, 2020). If achieved, such a shift would lead to significant savings of CO_2 emissions for heating our buildings. In Germany, for example, the use of geothermal technologies saved 3.5 million tonnes of CO_2 equivalent in 2021 (BMWi 2021 in Abesser and Walker, 2022).

As we expand our use of geothermal energy, it is essential to have a good understanding of this subsurface resource and the potential effects of its increased use. Here we discuss the capabilities and latest results from the UK Geoenergy Observatories – two subsurface facilities that enable the research and innovation required for the clean energy transition.

Ground source heat pumps

In 2021, the UK had an estimated 43,700 installed ground source heat pump (GSHP) systems (Abesser & Jans-Singh, 2022). From horizontal, closed-loop systems buried a few metres deep to open-loop boreholes that reach depths of around 500 m, GSHPs are a means of boosting the shallow, low-temperature (10-25°C) geothermal energy resource to temperatures of 40-70°C needed for heating and hot water. GSHPs make use of the stable subsurface temperatures derived from solar energy that is stored in rocks and soils close to the surface, elevated temperatures beneath cities due to the 'urban heat island' effect, and the geothermal gradient – higher temperatures at depth generated by radioactive decay within Earth and its residual heat.

Where aquifer properties allow for greater flow and thus heat transfer, shallow geothermal systems can be used to supply district heating networks that are shared between a number of homes and buildings that utilise GSHP technology. Gateshead heat network and the planned Seaham Garden Village are examples of large-scale projects in north-east England. Developed by local authorities, private developers and with the Coal Authority, these projects have capacities of around 6 MW and supply up to ~1,500 buildings each.

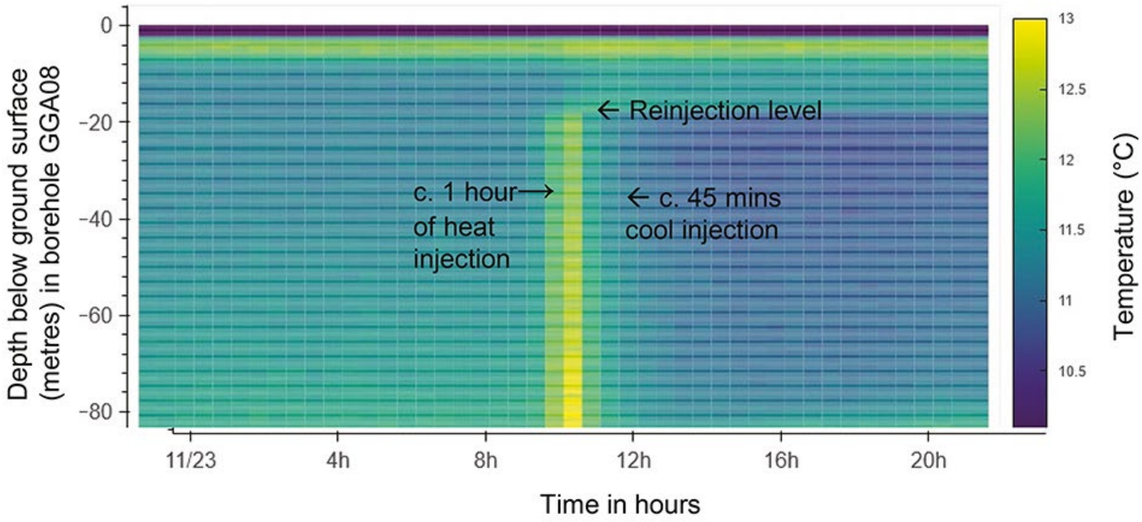

Figure 2: Distributed temperature sensing profile at Glasgow Observatory borehole GGA08. This temperature sensing profile was taken during initial geothermal infrastructure commissioning works. The profile images heat and cool injection into borehole GGA08 (see Fig. 1) using fibre-optic cables permanently installed on the outside of the casing. BGS©UKRI 2023

The same technology can be used in reverse, to cool buildings in warmer months or those with excess heat, such as data centres. Using the subsurface to cool buildings means adding heat to the underground. The subsurface has large thermal capacity, so there is considerable interest in underground thermal energy storage (or the thermal geobattery) as a means of combatting the intermittency of renewables, varying inter-seasonal heat demands and ensuring the efficient and sustainable use of the thermal resource. A successful example is the mine water scheme at Heerlen in the Netherlands, which has developed into a fifth-generation district heating and cooling network that uses both buildings and the subsurface mine water system to supply and balance heating and cooling demands.

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Researching subsurface change

But what happens in the subsurface when many people start using this shallow geothermal heating, cooling and thermal storage capacity? How long will the resource last and will there be environmental impacts? Large growth of the sector is on the horizon but there are gaps in our knowledge of thermogeology applied at scale, in a variety of geological settings and over tens of years of operations. On this shallow, warm frontier, geoscientists are needed to provide new data and knowledge on the size and sustainability of the resource, the impacts of the heat-flow cycling repeatedly discharging and recharging the thermal geobattery, and the ways to reduce cost and risk for efficient transfer of heat via geo-engineering infrastructure.

One part of the solution is at-scale research and innovation infrastructures that complement commercial schemes. The £31 million UK Geoenergy Observatories (www.ukgeos.ac.uk) is a major capital investment in subsurface research facilities by UK Government, through the Natural Environment Research Council. The Observatories comprise the Glasgow Observatory, focused on mine water geothermal, which became fully operational in spring 2023 and the Cheshire Observatory, focused on aquifer thermal energy storage and ground source heat, that will be operational in 2024. A state-of-the-art core scanning facility at British Geological Survey (BGS) Keyworth also forms part of the UK Geoenergy Observatories.

The BGS is delivering the observatories and will operate them for the science community. Here, academia, industry and regulators can use flexible arrays of boreholes, monitoring and geothermal equipment (see Table 1 online) to gather new data and knowledge on subsurface change, whilst optimising geo-engineering and environmental impacts. The observatories will also allow new equipment and techniques to be trialled, and people can visit to see what low-temperature geothermal looks like.

The Glasgow Observatory

Located in the east end of the city, the Glasgow Observatory enables investigation into mine water heating, cooling and thermal storage. It includes 12 boreholes, four fenced compounds and a flexible, sealed, open-loop geothermal infrastructure for taking heat out of, or putting heat into, two levels of flooded, abandoned coal mine workings within Carboniferous Coal Measures (Fig. 1). Downhole fibre-optic, geoelectrical and hydrogeological sensors are installed to monitor both ongoing environmental change and responses to abstraction/re-injection of warmed or cooled mine water. The wider environment is monitored via permanently installed soil (ground) gas probes, near-surface gas monitoring, seismometers, and reflectors to increase the precision of InSAR for ground motion, along with a series of soil gas, soil chemistry, surface and groundwater chemistry surveys. Pressure, temperature and other sensors are installed across the geothermal pipework and equipment to quantify performance and heat losses. Extensive, openly available characterisation and environmental baseline monitoring data are available online – users can design their own investigations, test new methods and technologies over a lifetime of 15+ years.

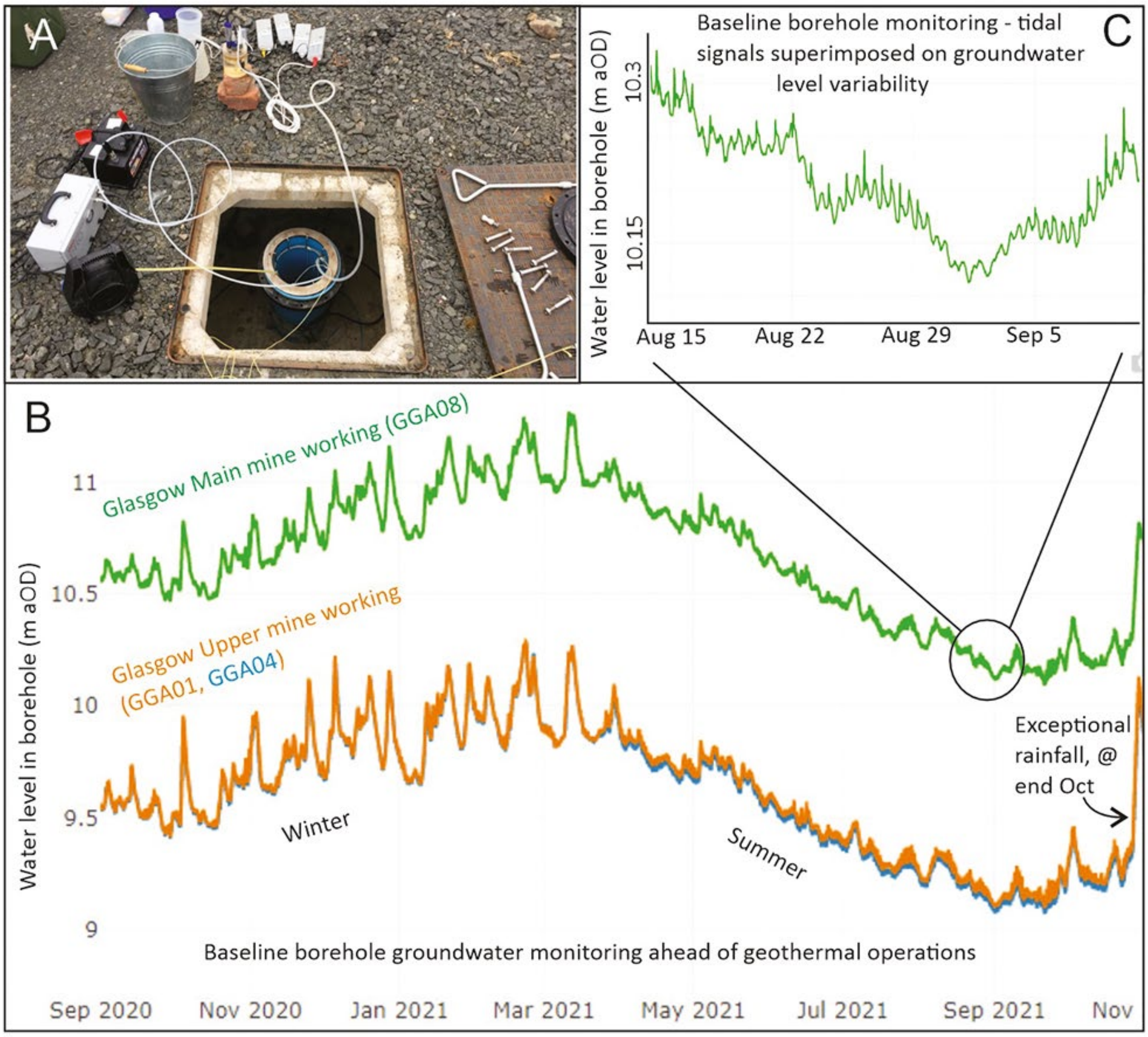

Figure 3: Baseline monitoring of groundwater levels. (A) Water sampling from a borehole. (B) Over a year's groundwater level monitoring data from three boreholes (GGA01, GGA04, GGA08) screened across mine workings. (C) Detailed variability in groundwater level in borehole GGA08. (m aOD, metres above Ordnance Datum). BGS©UKRI

Challenges for mine water heat

The capital costs associated with drilling, constructing and test pumping new boreholes for mine water heating schemes can be high. There is technical risk associated with successfully screening across at least two mine workings that deliver a long-term high flow rate and/or re-injection capacity, at an appropriate temperature, and suitably separated in the mine system.

Mine abandonment plans outline the extent and depth of the mine water reservoir targets. However, the anthropogenic aquifer is commonly highly variable, ranging from open roadways and voids, through backfill and collapsed strata to fractured rock and pillars of intact coal. The mine water boreholes at the Glasgow Observatory are screened across a variety of these 'reservoir' types, allowing investigation into their hydrogeological and thermal properties for both heat abstraction and thermal storage – parameters that are currently poorly documented. A better understanding of these parameters will help inform the location targets for drilling and aid technical risk assessments.

Initial test pumping results from the Glasgow Observatory are encouraging. They suggest a representative setting for investigating and quantifying flow and thermal processes for mine water heat energy schemes more broadly. For example, short-test pumping (e.g. 25 litres per second of water at 12°C for five hours) showed that three boreholes in the same mine working, but screened across different reservoir types, all had similar transmissivities (essentially the rate water passes through a unit) of about 1,000 m^2 per day. Additionally, pressure responses suggest good reservoir connectivity within the same mine working, and limited connectivity between the two levels of mine workings.

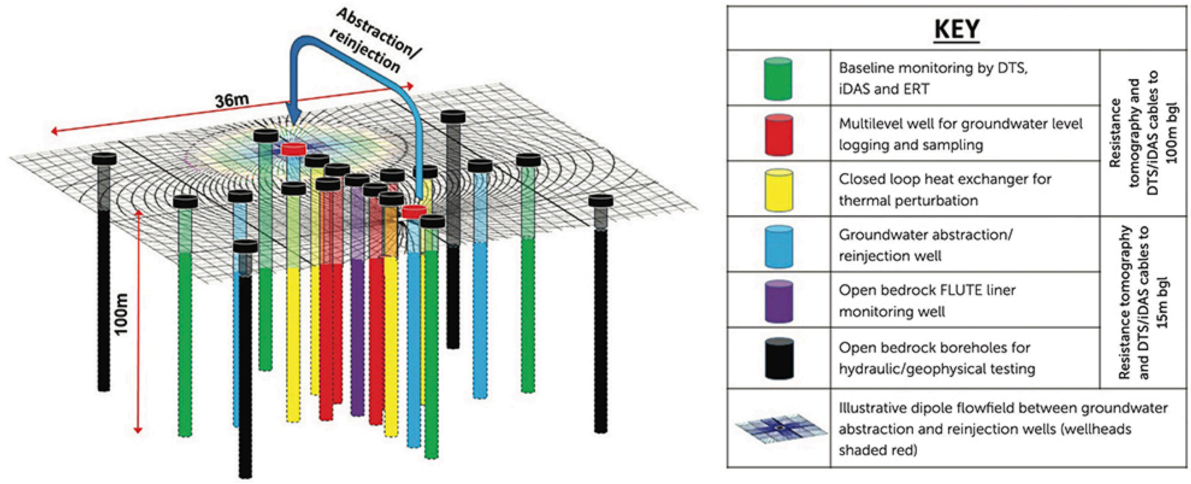

Figure 4: Summary figure of the Cheshire Observatory borehole arrays. Blue arrow highlights how boreholes could be used for abstraction and re-injection (m bgl, metres below ground level; DTS, distributed temperature sensing; iDAS, acoustic sensing; ERT, electrical resistivity tomography). BGS © UKRI 2022

Monitoring infrastructure

For regulation purposes and security of supply to customers, it is critically important to understand the thermal behaviour, reservoir connectivity and rates of breakthrough, as well as heat depletion or recharging over timescales of days to years. Monitoring infrastructure at the UK Geoenergy Observatories allows us to track, image and quantify heat and flow movements underground, and to characterise the volumes of water and rock. For example, downhole fibre-optic cables allow for distributed temperature sensing and provide a baseline time-series of subsurface temperature. Initial measurements indicate that below a zone of seasonal fluctuation, temperature increases at a rate of approximately 1.3°C per 100 m. While more data analysis is needed over longer time periods, the utility of the monitoring technology can be seen in the initial geothermal commissioning, where the temperature sensors reveal pulses of ‘hot’ and ‘cool’ in a mine water borehole (Fig. 2).

A range of ‘baseline’ monitoring of the urban, anthropogenically altered environment has been undertaken at the Glasgow Observatory before geothermal operations commence. Urban centres commonly grew up around mines in the coalfields, leading to co-location of heat demand with the potential heat resource. These communities have lived experience of mining and its impacts, such as rising groundwater post-abandonment. Potential environmental impacts are an important factor in regulatory approvals and public acceptance of a new technology.

For example, baseline monitoring highlights clear seasonal variation in groundwater levels (Fig. 3B). More detailed analysis reveals the influence of tides, particularly solar and lunar daily tidal influences (Fig. 3C). It is important to identify these centimetre-scale, natural fluctuations in groundwater so that we can distinguish changes related to geothermal pumping. Soil gas probe data also reveal daily and seasonal fluctuations related to naturally occurring biological processes, and ground motion studies show that while there are some areas of subsidence related to settlement of the built environment, overall the ground is stable. Additionally, analysis of water and rock samples reveals isotopic and carbon signatures that could be used to trace connectivity within the aquifer or monitor biogeochemical reactions that might interfere with geothermal operations (such as the build-up of microorganisms that can result in clogging of pipes and heat exchangers).

Initial characterisation and monitoring shows that the geology and hydrogeology of the Glasgow Observatory is representative of legacy coalfields in the UK. As such, investigations carried out here using flexible infrastructure to measure, quantify and calibrate subsurface responses to heat-flow changes, as well as to test new equipment, should be transferable to other locations.

The Cheshire Observatory

The Cheshire Observatory focuses on subsurface energy storage, principally aquifer thermal energy storage. Currently in construction, 21 boreholes are being drilled to around 100 m depth in the Triassic Sherwood Sandstone (Fig. 4). The boreholes will be equipped with a range of advanced sensors for 3D imaging of subsurface processes in real time, multi-level groundwater monitoring and hydraulic control, and heating and cooling of the subsurface. This at-scale experimental infrastructure will provide an unparalleled dataset on the geological environment, which will allow optimisation of design and operations for shallow heating and cooling. The opportunity to characterise and monitor in situ processes at this site at a range of scales will also be highly relevant to other geoenergy technologies including hydrogen storage and CO_2 storage.

Understanding how the rates and processes of heat transfer are influenced by geological variations and by adjacent heating or cooling boreholes is a key area for research. These factors impact the design of future boreholes, and the size and sustainability of the thermal resource. The Cheshire Observatory will have the capability to track and image a thermal plume and groundwater responses in 4D (across a depth range and through time). Thermal plumes will be drawn through the intensively instrumented central part of the monitoring array using the four groundwater abstraction/reinjection wells (Fig. 4, coloured blue). Fractures were identified during construction, providing scope to investigate the influence of both porous rock media and fracture flow in controlling flow and thermal processes.

Digital twins

Digital representations of a real-world physical system or process can be used to simulate testing, monitoring and maintenance. Such digital twins, which incorporate a range of monitoring data into predictive models, are increasingly being developed for management of the subsurface and geoengineering infrastructure. The combined geophysical, groundwater and thermal monitoring technologies at the Cheshire Observatory will provide a unique capability for advanced monitoring, feeding into data science applications and digital twins for heating and cooling. The first multilevel monitoring well, which was installed at the start of drilling, is already providing important insights into the effect of drilling and thermal well installation on aquifer hydrogeology, for example, variations in groundwater level (see figure 5 online).

Geothermal well head at the Glasgow Observatory (BGS © UKRI)

Geothermal potential

Our shallow subsurface resources can help to decarbonise and decentralise the heating and cooling of our buildings, and provide heat storage to balance demand, thereby increasing the resilience of our energy supply. Realising this potential will mean addressing socio-economic, regulatory and technical challenges through measures such as target setting, risk and legislative support, heat planning and zoning, increased data availability, technical skills and innovation support.

The UK Geoenergy Observatories have been designed to increase scientific understanding of subsurface behaviour and its response to rock-water heat and flow changes in unprecedented detail, thereby helping us to plan the sustainable development of our geothermal resources. The observatories also serve as places to innovate to improve geothermal efficiency, and reduce cost and uncertainty. We encourage researchers working across geoscience, engineering, environmental and social sciences, economics and policy to get in touch to discuss their ideas. Contact us at: ukgeosenquiries@bgs.ac.uk

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Further reading

A full list of further reading is available at geoscientist.online

• Abesser, C. & Jans-Singh, M. (2022) 2021 United Kingdom Country Report, IEA Geothermal; iea-gia.org

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• Monaghan, A. A, et al. (2022) Time Zero for Net Zero: A Coal Mine Baseline for Decarbonising Heat. ES^3 (2).