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Initial insights on the safe access of abandoned mine shafts for heat storage

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ABSTRACT

Space heating, cooling and hot water make up approximately half of global energy consumption in buildings. To ensure a responsible and sustainable energy transition, existing low-carbon thermal energy resource opportunities should be utilized for both supply and balancing of heating and cooling systems. Given the growth of population centers around former and existing mining communities in the UK, abandoned and flooded coal mines are becoming increasingly recognized as a potential resource for heat energy production and thermal storage. This paper provides insights from desk and field studies appraising the potential for drilling into an abandoned and capped mine shaft that is being explored for thermal energy storage at the former Comrie Colliery, Fife, UK. We describe results of the initial site investigation, including data availability challenges, field work, miner testimonies, and future planned activities. This work feeds into development of a site characterization approach which will minimize exploration and operational risks for development of mine shaft energy storage systems.

1.0 INTRODUCTION

As energy generation becomes progressively dominated by renewables and energy distribution becomes more decentralized, storage of thermal energy will become increasingly critical for effective energy management. In 2018, 46% of the total global energy demand was for space and water heating (Benz *et al.,* 2022). In the UK, domestic heating accounts for 29% of total energy demand with 78% of this energy supplied from natural gas (Slorach & Stamford, 2021; Kelly & Cowi, 2021). In terms of domestic energy, space and water heating in Europe accounted for 75% of demand in 2022 (Benz *et al*., 2022).

The UK has a Net Zero target of a reduction in current emissions to 1990 levels by 2050 (BEIS, 2019). To achieve this, there needs to be a 24% decrease in CO_2 emissions from the housing sector alone (Bennadji *et al*., 2022). Increasing the energy efficiency of new build and existing UK housing stock is an important step, but responsible use of heat energy will be a critical factor in meeting this target.

The intermittent nature of renewable energy generation poses a challenge for efficient energy distribution. Between 2020 and 2021, £350 million was paid in constraint payments to wind farms in Scotland to curtail 5 TWh of wind energy and avoid overwhelming the UK National Grid power network (Agbonaye *et al.*, 2022). The act of not exploiting readily available renewably sourced energy is counterintuitive for the UK's Net Zero goal, as this curtailed energy could be stored, or the money given in wind curtailment payments could be better used for insulating one of Europe's most energy inefficient housing stocks (Bennadji *et al*., 2022; Holmes *et al*., 2019) and reducing fuel poverty.

Thermal energy storage could play a significant role in meeting Net Zero targets by increasing energy efficiency and making use of waste heat generated from agricultural, industrial and energy production processes. It would also be possible to take, convert and store energy that would otherwise remain untapped from renewable power generation. Stored heat could be used at times of increased seasonal or daily peak demand, providing more balance for energy systems, more sensible and sustainable utilisation and reducing dependency on fossil fuels. One of the most promising ways to link storage systems to end consumers would be via district heating networks, which in Northern China deliver 80% of the total heat demand in urban spaces (Zhang *et al.*, 2021).

Several thermal storage options are currently available and deployed at a range of scales, including aquifers, pits, tanks, and borehole arrays. Energy storage in mine workings has been suggested in the past, with publications mentioning compressed air storage, and using mine shafts as locations to house large hot water tanks (Bartela *et al.*, 2022; Ghoreishi-Madiseh *et al.*, 2017). Another option that has not received any attention thus far is mine shaft thermal energy storage (MSTES). The main interest in development of low-temperature mine water geothermal (MWG) systems has been on their direct use for low-carbon heating schemes. However, flooded mines also provide an exciting opportunity for thermal energy storage as they are common across the world and often situated below or near urban and rural population centers that are home to former and current mining communities. Mine shafts are often key components of mine infrastructure and where they haven't been backfilled on abandonment, they represent large void spaces. They are typically of well-known location and dimension and can contain mega-liter volumes of water kept relatively well insulated by the shaft lining and surrounding geology.

The required conditions needed for thermal energy storage in a mine shaft is firstly a large volume of water within the shaft, as this is the storage medium. If the shaft has been backfilled with material, this will affect the amount of energy that can effectively be transferred to the water within the shaft, however if the porosity is high enough, the site may still be viable for thermal energy storage.

The shaft also requires a lining that does not contain any large cracks or sufficient degradation as to allow fluids and heat to escape easily (Alva *et al.*, 2018). Equipment abandoned in the mine will have a negligible impact on the amount of available water, however it may have an impact on the water chemistry due to the effects of rusting and also may impede the use of logging equipment due to the risk of entanglement.

If sensible thermal energy storage (Fernandez *et al*., 2010) could be demonstrably proven in flooded shafts there are thousands of towns and cities worldwide that could exploit these voids to limit waste heat and balance energy supply, including 9 out of the 10 largest cities in the UK (Coal Authority). Equivalent volumes of warm water storage above ground, while potentially more thermally efficient than MSTES, would require significant land take and have an undesirable visual impact for highly populated areas.

Our study focuses on characterization of a flooded mine shaft in the east of Scotland (Figure 1), which is under investigation to better understand the potential role of MSTES in the transition from fossil fuel dominated energy systems to equitable and sustainable low-carbon replacements. This paper provides insights from our initial investigations at the former Comrie Colliery, detailing data gathering, field work and testimonies from retired miners. The colliery was active from 1936 – 1986. The decommissioned site is now owned by Comrie Development Company Ltd and is under consideration for MWG and MSTES as part of future redevelopment plans.

Site characterization has thus far focused on Comrie No.1 Shaft, which was used to extract coal from the mine to the surface during the colliery's operation (Figure 2). According to abandonment records this shaft was left unfilled and was capped near surface. Following mine closure and cessation of pumping 36 years prior to our work, substantial water table rebound is likely to have taken place and created the opportunity for thermal energy storage within the shaft.

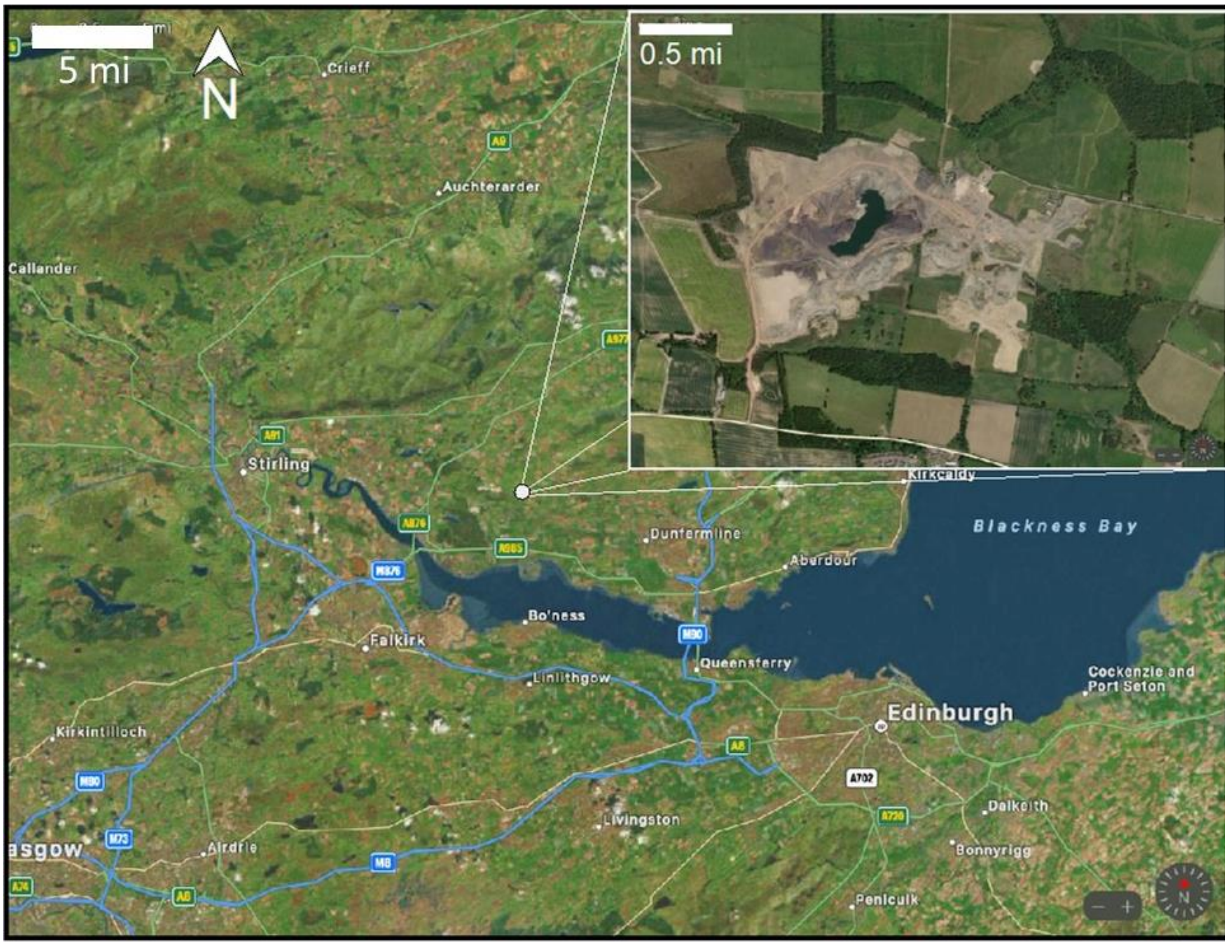

Figure 1: Map showing location of the former Comrie Colliery site, Fife, UK. (after Copernicus Landsat, 2021)

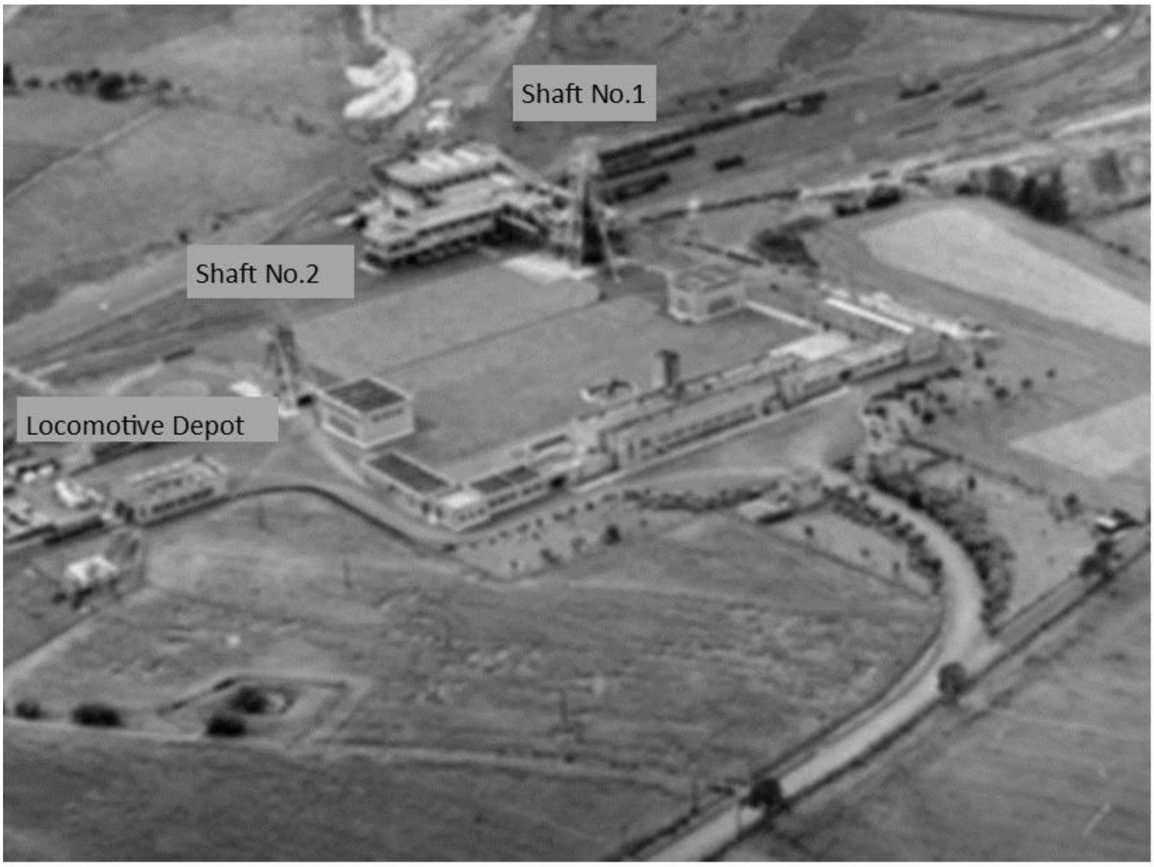

Figure 2: Aerial photograph of Comrie Colliery taken in 1960, displaying the layout of the site during operation. (After Comrie Development Company, 2023).

Following cessation of mining and abandonment of the site, most of the surface infrastructure was demolished and the site was flattened, adding a layer of made ground above much of the original surface level. The only building that remains standing in the present day is the former locomotive depot, situated middle left in Figure 2. There are no remnants of shaft infrastructure present at modern day surface level. The lack of modern surface expressions, presence of post-abandonment made ground, and paucity of detail in the site abandonment documentation poses a challenge for gaining access to the Comrie No.1 Shaft. The following sections details work completed so far and future plans to safely access the shaft for further resource assessment.

2.0 SITE CHARACTISATION OF THE COMRIE NO.1 SHAFT

The overall aim of this project is to assess the potential for heat storage within the Comrie No.1 Shaft. To achieve this, the shaft will have to be accessed for hydrogeological investigation via an exploratory borehole. Before any drilling activities could be effectively planned, the exact location of the shaft, condition of the shaft completion works, and depth of present-day overburden above the shaft had to be determined.

The starting point was acquisition of colliery plans to better understand geometry of the underground infrastructure. This allows for assessment of potential pathways for water and heat through the mined void space and engineering infrastructure. Most UK mine plans are held by the Coal Authority (TCA). For Comrie, information held by TCA was limited, so further documentation was acquired from the Scottish Mining Heritage Museum which provided detail on the layout of roadways around the shafts. The acquired digitised mine plans also allow connectivity with other workings in the area to be understood, as connections to other collieries may have effects on water flow and heat loss depending on the hydrological behavior of the system.

The documented OS grid reference of Shaft No.1 is 300529, 690999 and ‘The Layout and Equipment of Comrie Colliery, Fifeshire’ (Reid *et al*., 1939) records a total depth of 419m and diameter of 6.1m for the No.1 Shaft, giving a total shaft volume of c. 11,600m^3. This shaft was used to wind coal from a depth of 390m to the surface (Figure 3) using two skips (large, open top containers), measuring 3.8m long and 1.2m wide. It was common practice to leave such infrastructure within shafts during mine abandonment, but the vertical location of these skips for Shaft No.1 is unknown from available historic records.

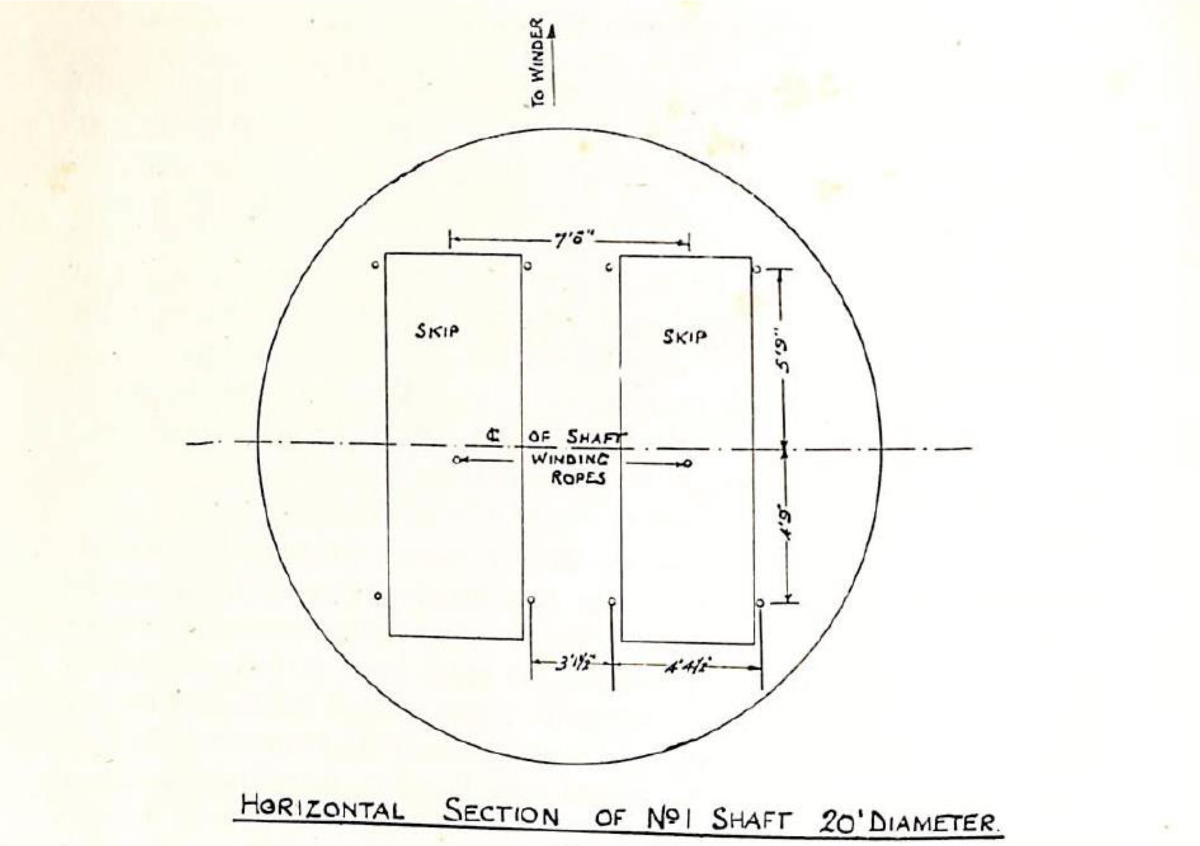

Figure 3: Sketch of the horizontal section of Shaft No.1 at Comrie Colliery (Reid *et al.*, 1939).

Various historic UK specifications exist for the safe abandonment of mine shafts. The Mines and Quarries Act 1954 states there had to be an effective 'plug or barrier to prevent accidental entry' but did not include reference to appropriate design standards. TCA information is limited to the declaration that Shaft No.1 was treated with a "concrete cover at surface level", suggesting that it was completed with a competent cap. No specific shaft abandonment plan or designs of abandonment measures are available. Therefore, the characteristics of any cap on Shaft No.1 is uncertain. In addition to this, there are no available plans for the abandonment of the Colliery. Therefore, an intrusive investigation into the shaft is the only way in which to prove that the shaft has not been infilled with solid waste material and contains enough water to be used for MSTES.

3.0 IDENTIFYING KNOWLEDGE GAPS

The knowledge gaps that were identified mainly centered around the abandonment of Comrie Colliery. As there have been historic inconsistencies with both the level of detail recorded in mine plans and the gathering of plans into TCA custodianship, it is possible that future projects looking to use abandoned mine infrastructure for MWG or MSTES purposes will require additional sources of information.

Although an excellent starting point, the data acquired for a desk study in some cases may not have the detail or accuracy required to provide confident understanding of the mine layout, flooding status or abandonment measures. Archived datasets typically include the locations of mine entrances, spine roadways and underground workings, as well as depths to specific coal seams. During the study of available Comrie data, it was noted that, in some instances, digitized mine maps did not accurately describe subsurface infrastructure or missed important information, such as roadway depths and details of mine abandonment, that would be useful to assess feasibility of MSTES at this location. The available data only gives the extent of the workings, for example the types of support used for roadways and where roadways have been closed off are not included in the dataset. In addition, there is no information on any collapses or stoppages within the underground workings, which would effect fluid and heat flow within the system. For the purposes of intrusive investigations into the shaft, it is important to know if spontaneous combustion had occurred at the site due to risks associated with releasing gasses to the surrounding environment.

For Comrie Colliery, there is uncertainty as to where the shafts are located, whether they have been infilled (and with what material) and how they were capped (if at all), and other factors such as how engineered infrastructure, such as shaft skips and fire doors, may have been left upon mine abandonment. These uncertainties need to be addressed as best as possible before any intrusive investigations can take place.

4.0 OVERCOMING KNOWLEDGE GAPS

To overcome the identified gaps in knowledge, we deployed non-invasive geophysical surveys to help identify exact shaft locations and performed semi structured interviews with former Comrie miners to gain first-hand information about the colliery and clear up discrepancies in available records.

4.1 Geophysical Surveys

Ground Penetrating Radar (GPR) and Electromagnetic surveys were carried out to locate and assess the near surface characteristics of Shaft No.1.

Ground penetrating radar is a near- surface geophysical technique that uses electromagnetic (EM) fields to detect structures and features within the subsurface. This is achieved by emitting EM signals. These signals penetrate the subsurface and are then reflected or scattered by differences in impedance within the subsurface and detected by a receiver (Annan, 2005). These detected signals form a representation of the subsurface that can be interpreted. This technique was used in an attempt to find the cap of Shaft No.1 by using a Mala X3M GPR with an antenna frequency of 500MHz, achieving a penetration of up to 5m.

To remove the accumulation of made ground and have a clearer survey of Shaft No.1, an excavator was used to dig a narrow~3m deep trench which reached the concrete pad representative of the original surface level during active mining operations. The survey taken showed greater quantities of interference as the electromagnetic waves reverberated and were producing a ringing phenomenon in the dataset. This effect is mostly attributable to the presence of metal in the subsurface (Atef & Rashed, 2023). This was supported as high levels of metallic waste such as steel winder cable and waste rebar were found at this level. The results gave no clear indication of shaft-related void space or concrete cap beneath the excavated trench.

This trench was widened to investigate further. The excavation uncovered a large concrete pad (Figure 4), and one of the foundations of the conveyor belt used to take coal from the shaft to the processing plant. Another GPR survey was conducted with the same parameters as above, as it was suspected that this concrete structure could have been the cap for Shaft No.1, or may be part of the infrastructure around the shaft. From the data acquired, it is still uncertain whether the mine shaft void is present.

In addition to GPR, Electromagnetic Imaging was used. EM utilizes electromagnetism to induce an electric current in the earth. This current is affected by heterogeneities in the subsurface. The magnetic field produced by these secondary currents is measured using receiver coils (Styles, 2012). Acquired information can then be digitized and interpreted. Again, from this dataset it was not clear if a mine shaft void was present. More site investigation work is therefore required to accurately pinpoint the location and condition of the subsurface around the No.1 Shaft.

Figure 4: Photograph of the exposed concrete pad after excavation and GPR being set up for a survey.

4.2 Miner Testimonies

To counter the gaps in information left by the limited mine plan and abandonment records, we conducted interviews with retired miners who had worked at Comrie Colliery. These miners had memories of the shaft and mine infrastructure, which added rich detail to the available information. The interviews took place following University of Strathclyde ethical guidelines and a risk assessment was completed. Coal mining was a dangerous, sometimes deadly, vocation. None of the questions chosen for this study alluded to specific disasters, however topics such as shaft collapse, water chemistry, presence of gas and fire safety formed part of the interviews. All questions were reviewed by the project team to ensure there were no upsetting or controversial topics included in questioning. Care was taken to remind the subjects that they could stop the process at any time, and they were under no obligation to be part of the study if they did not want to be.

The interviews confirmed that there were no significant roof collapses during mining operations. Where sections had been completed (i.e., all coal had been extracted), roadways were stopped off with cinder block walls with U-pipes installed to prevent spontaneous combustion. This precautionary measure was made despite the fact that spontaneous combustion had never occurred during operations at Comrie colliery.

From the testimony of an engineer who oversaw the abandonment of the shafts at Comrie Colliery, the skips and cages used to take men and coal respectively in and out of the mine, were left in the shafts. There were two lifts in each shaft. One was brought to the surface and supported with steel girders while the other was at the bottom of the shaft. When the shafts were abandoned, the steel ropes that supported the lifts were cut and the lift at the bottom of the shaft was allowed to free fall into the sump (drainage pit at the bottom of the shaft) along with the cut cables. The skip at the surface was subsequently extracted from the shaft. The shaft entrances were then covered with a steel plate cover. Abandonment was then taken over by an unknown civil engineering company, who is believed to have replaced the steel plates with a concrete cap, having first excavated the earth around the shaft. No equipment was salvaged before the abandonment due to it not being economically viable.

From the testimonies, one interviewee noted that it was reported to them that Shaft No.2 was backfilled with co-excavated red shale mining waste, but as far as they were aware Shaft No.1 was left unfilled. Another interviewee told us that no preparation for backfilling had been carried out, as there would need to be a blockage at the bottom of the shaft to stop infill material escaping at the shaft bottom to connected roadways. This was never done.

5.0 NEXT STEPS

The next field activity at the site will be an Electrical Resistivity Tomography (ERT) survey. This technique will allow for deeper ground imaging and mapping of variations in subsurface resistivity. Any zones or features with high resistivity may indicate void space or concrete structures, as these features do not conduct electricity well. Once the location of the shaft is confirmed and the nature and situation of its cap and overburden are established, an exploratory drilling strategy will be developed. If a borehole can be successfully completed through the cap a borehole camera will be used to inspect the shaft void space and condition of its concrete lining. The presence of water will be established via camera inspection and a dipmeter, and if possible, water samples will be taken using bailers and hydrochemically characterized to assess the mine shaft environment.

6.0 CONCLUSION

The Comrie No.1 Shaft is under investigation for use as a potential mine shaft thermal energy store (MSTES). Due to a lack of available Comrie Colliery abandonment information and uncertainty regarding the location of Shaft No.1, a range of methods have been utilized to better understand the site, the present-day condition of the shaft, and its surrounding ground properties so that the shaft can be safely accessed with an exploratory borehole. Non-intrusive Ground Penetrating Radar (GPR) and Electromagnetic surveys have enabled initial ground truthing, and further Electrical Resistivity Tomography (ERT) work will be carried out to increase confidence in Shaft No.1 location. Additional assessment of near-shaft ground conditions will feed into a drilling plan to access the shaft. If a successful borehole is completed, shaft condition, including the integrity of the concrete lining and presence of water will be assessed. The lack of available data for Comrie Colliery has been partially addressed via interviews with ex-miners, resulting in valuable information on subsurface architecture and operation practices. Completed and future work will allow assessment of thermal storage feasibility in the Comrie No.1 Shaft, potentially leading to practical integration of MSTES into a low-carbon development plan for the site of the former Comrie Colliery.

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