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The Thermal Resource of Mine Waters in Abandoned Coalfields; Opportunities and Challenges for the United Kingdom

Gareth Farr[1] and Jon Busby[2]

[1]British Geological Survey, Cardiff University, Main Building, Park Place, Cardiff, CF10 3AT, UK

garethf@bgs.ac.uk

[2]British Geological Survey, Environmental Science Centre, Keyworth, Nottingham, NG12 5GG, UK

jpbu@bgs.ac.uk

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ABSTRACT

In the absence of high temperature hydrothermal zones, the most promising geothermal opportunity in the United Kingdom (UK) is direct use of low enthalpy resources. In order to advance understanding and knowledge of direct use the UK participates in Working Group VIII, "Direct Use of Geothermal Energy", a collaborative task of the International Energy Agency Geothermal Technical Cooperation Programme (IEA Geothermal). The working group advances direct use knowledge through workshops and publications of good practice and case histories. This review paper contributes to this objective with a discussion on the geothermal potential of the heat contained within the waters of disused mines, which has particular relevance to the UK.

It may come as a surprise that mine waters from abandoned coal mines represent a large geothermal resource and offer a number of advantages for direct use geothermal. Coal mining has created enhanced permeability in rocks of usually low permeability making available a large body of readily accessible groundwater. In some cases convection within the mine water network will allow warmer water to rise from depth to the near surface. In the UK, coal mining often resulted in the establishment of urban areas creating a ready market for this low grade geothermal heat. This legacy from hundreds of years of coal mining is just starting to be developed, but there are barriers to be overcome. This paper discusses, from a UK perspective, the opportunity presented by mine waters, the extent of the resource, legislative issues and the advantages and disadvantages of mine water geothermal systems.

1. INTRODUCTION

In the UK about 13% of our total greenhouse gas emissions are derived from space heating for domestic buildings (BEIS 2017). Given that 80% of domestic heat demand is supplied by natural gas (Watson et al., 2019) it is clear that decarbonisation of domestic heating is needed for the UK to meet its greenhouse gas emission targets (BEIS 2017). As a result, the UK Chancellor of the Exchequer announced in spring 2019 that from 2025 all new homes must be heated by low-carbon heating systems, i.e. fossils fuels will be banned (Spring Statement 2019). This change will apply to all new builds from 2025 (including commercial buildings, public buildings, social housing, etc.) and hence it is anticipated that the installation rates for heat pumps, both air and ground source, will increase substantially.

In the absence of high temperature hydrothermal zones, the most promising geothermal opportunity in the United Kingdom (UK) is direct use of low enthalpy resources. Despite the increasing demand for renewable heat, in the UK, there is only around 3.5 MWth of direct use geothermal and around 29000 ground source heat pumps, with a total installed capacity of 520MWth (Curtis et al., 2019). In order to develop the geothermal industry in the UK and advance understanding and knowledge of its direct use, the UK participates in Working Group VIII, "Direct Use of Geothermal Energy", a collaborative task of the International Energy Agency Geothermal Technical Cooperation Programme (IEA Geothermal). The working group advances direct use knowledge through workshops and publications of good practice and case histories, including mine water geothermal.

Many local authorities and housing developers are already looking to include renewable heating systems in new developments and have become aware of the potential of the thermal resource within disused underground coal mines. However, they often find it difficult to acquire the information they need to understand the nature and potential of the resource and to gather enough information to write a business case for financing a scheme with inherent uncertainties compared to other renewable energy options. This review paper contributes to the objective of advancing knowledge and good practice with a discussion on the geothermal potential of the heat contained within the waters of disused mines, which has particular relevance to the UK.

2. NATIONAL AND REGIONAL RESOURCE STUDIES

Most of the UK's underground coal mines are now closed, but during their operational life time about 75 billion m^3 of coal was removed (The Coal Authority, 2019). Onshore coal resources in the UK are mostly of Carboniferous age although some coals occur offshore in the Lower Cretaceous and Jurassic strata (BGS, 2010). Historically, coal was mined both underground and in opencast pits. UK production peaked in 1913 at 287 million tonnes, however the industry started to decline rapidly in the early 1980s and by 2001 production was exceeded by imports of coal (BGS, 2010). Dewatering of underground coal mines was common practice in the UK, however as the collieries closed the pumps were turned off and the workings allowed to flood. As mine water levels rebounded, mine water outbreaks occurred across the country, often along river valleys (e.g. Figure. 1). These mine water outbreaks caused, and still cause, extensive pollution to surface waters. The Coal Authority, who have responsibility in Great Britain for disused coal mines have constructed 75 mine water treatment schemes across the UK to address this problem. Due to its long association with pollution events, mine water has been considered until recently, entirely as a liability, with few potential end uses.



Figure 1: Example of a gravity driven mine water discharge which are common across the UK's coalfields and often result in surface water pollution. Thermal energy could be recovered without the need for drilling at these sites. © British Geological Survey.

Figure 2 shows the location of underground coal mining overlain by urban areas within the coal mining regions. These urban areas present a large heat demand that could be met by sections of the disused mine networks, although it is likely that a large investment in heat networks would be required to exploit it. Any prediction of the estimated resource at a particular location will require local data on mine water abstraction rates and mine water temperatures as well as mapping of the underground workings to determine where any abstraction and injection boreholes would be located. There have been a number of regional and national estimates of the potential heat resource in abandoned coal mines. Wiltshire and Burzynski (2008) studied the potential in England and Wales where they identified around 1400 abandoned mines, of which 320 to 340 had sufficient information to make a resource estimation. Estimates of mine water flow rates were based on the number of men recorded as working underground. For the 320 to 340 sites the total estimated thermal energy was 1983 MW. Gillespie et al. (2013) considered the potential mine water resource in Scotland. From published groundwater pumping rates in mined areas, they concluded that if 4 boreholes were evenly distributed per km^2, then a reasonable estimate of yield would be 60 L s^{-1} km^2. If it is assumed that the temperature drop across the heat pump is 5^oC, then for the mined areas of Scotland the total heat resource would be around 6000 MW.

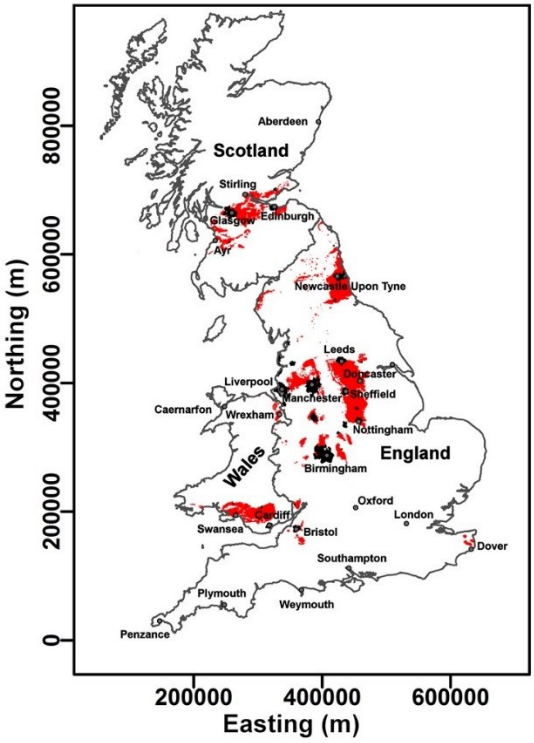

Figure 2: Extent of underground mining (red areas) overlain by urban areas (in black) for Great Britain. Some place names included for orientation purposes only. The data were compiled by Jones et al. (2004). Contains Ordnance Survey data © Crown copyright and database rights. All rights reserved [2019] Ordnance Survey [100021290 EUL]

The Coal Authority operate mine water treatment systems and pumping stations to ensure the former mines do not have an adverse environmental impact. At former colliery sites where this is necessary, the infrastructure to abstract the mine waters is already in place and exploitation of their thermal potential is both an environmental and economic benefit. Bailey et al. (2016) considered 64 such operational sites and estimated that as much as 47.5 MWth of thermal energy was available, based on a temperature drop of 4^0C across the heat pump. Farr et al (2016) estimated that between 42 and 74 MWth of heat could be recovered from gravity driven discharges in the South Wales coalfield. However this estimate doesn't incorporate the potential for heat storage, which if managed properly could result in balanced systems where negative thermal breakthrough could be avoided and a greater amount of heat could be recovered. The Coal Authority estimate that across the UK there is 2.2 GWh of heat in abandoned coal mines in the UK (The Coal Authority, 2019).

3. TEMPERATURE OF COAL MINE WATERS

Measured temperatures of abandoned mines are required to support national resource assessments and for use in early stage feasibility studies, underpinning the planning and design of new ground source heating schemes. In the UK a mean geothermal gradient of 28 °C/km has been calculated for the upper 1 km of crust across all geological strata, including data from some coal mines (Busby et al., 2011). It may be reasonable to apply this figure when making high-level resource assessments for the UK's coalfields, however it may be less useful if applied to individual sites, because measured temperatures in mines are known to be variable.

It has long been known that there can be significant heterogeneity in measured underground strata temperatures in operational coalfields and more recently this has also been observed in post closure flooded mine waters. Temperature measurements collated from early studies related to the impact of heat on coal miners (e.g. Everett, 1882; Lebour, 1881; Graham, 1921-22; Jones, 1924; 1926; Prestwich, 1887) show that temperature ranges > 13°C were measured at similar depths across the UK's operational coalfields. Recent examples from post closure flooded coalfields report that measured temperature ranges > 20°C can occur at comparable depths (Farr et al., 2016). Figure 3 is a plot of temperature profiles measured through coalfields from across the UK that illustrates this heterogeneity. The significance of this variability needs to be better understood as it could potentially impact national or regional resources estimates and also the proposed design, depth and performance of ground source heat schemes in abandoned coalfields.

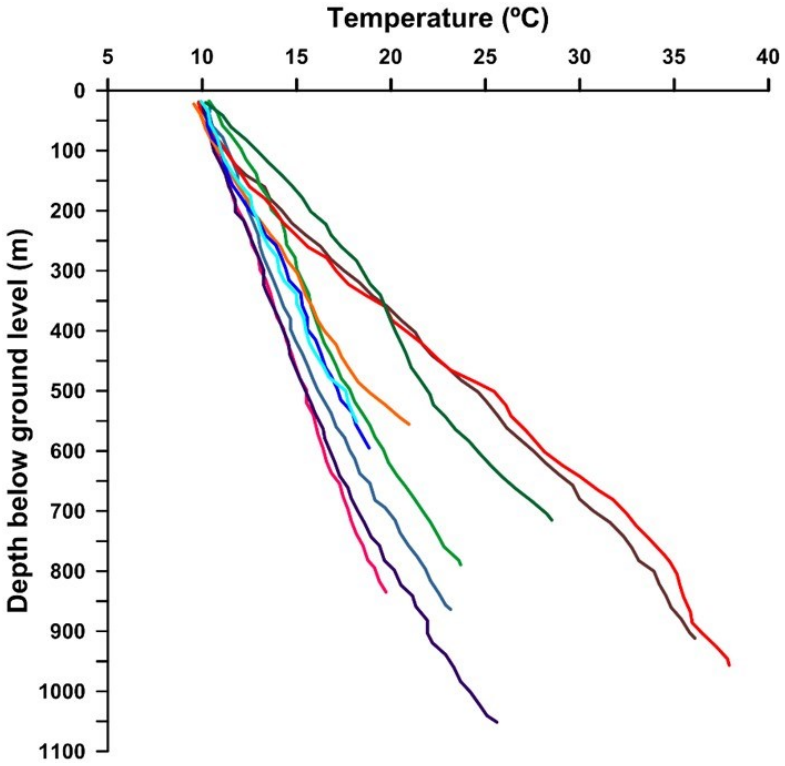

Figure 3: Temperature depth profiles illustrate the heterogeneity of mine water temperatures within the UKs coalfields (NCB 1982-1983 data held by British Geological Survey).

The UK requires national scale temperature maps of mine water in abandoned workings to allow local authorities, developers and planners to scope out the potential for coalfield heat recovery and storage. The controls of temperature in flooded mine workings are not fully understood and are likely to be driven by a multitude of factors including; depth, structural features (e.g. faults), thermal properties of overlying strata, local and regional groundwater regimes, mine water residence time, microbial respiration and exothermic chemical reactions. Better understanding the controls of heat in abandoned mines will allow them to be managed sustainably and to appropriately regulate heat recovery and storage.

4. SUSTAINABLE EXPLOITATION

Low enthalpy mine water in abandoned coal mines can be sustainably exploited using proven open loop, and occasionally closed loop, ground source heat pump (GSHP) technology (e.g. Hall et al., 2011; Verhoeven et al., 2014; Banks et al., 2017). Recovery and storage of heat in abandoned coal mines presents a number of beneficial factors when compared to unmodified aquifers, including;

- **Proximity to demand:** Mining often took place in urban areas or the mining resulted in urbanisation. It is estimated by The Coal Authority, that 1 in 4 properties in the UK are located on abandoned coalfields.
- **Limited competition for resource:** Currently mine water has few if any uses in the UK, as poor quality water makes it unsuitable for potable, industrial or agricultural processes. Thus the use of mine water for heat recovery and storage is less likely to cause conflict with other groundwater users.
- **Enhanced hydrogeological properties:** Coal mines in the UK are often in geological strata of natural low porosity and permeability. However mining results in a network of connected shafts, galleries and adits with enhanced permeability and higher storage than the original host rocks.
- **Enhanced depth**: Mine galleries may extend to depths of up to 1km. Since groundwater will generally increase in temperature with depth, the connected pathways may result in warmer groundwater rising by convection.

Despite the benefits of using abandoned mines there are also challenges to sustainable use of this low enthalpy heat resource including;

- **The ownership and definition of heat** in the subsurface needs to be addressed and adapted into UK law and regulations (Abesser et al., 2018). Without regulation certainity of the heat in the subsurface it is possible that the sustainable development of heat recovery and storage could be negatively impacted or appear less attractive to investors and developers.
- **Licencing and permitting** of ground source heat recovery in coalfields requires a multi-party approach between The Coal Authority and the environmental regulator. Statutory consultation times can be up to 4 months and are often much longer. Long determination periods for permits and licences are off putting for investors and developers, which is likely the main reason for the small amount of open loop systems installed in the UK.

5. OPERATIONAL CASE STUDIES IN THE UK

There are number of options for heat exchange between the mine waters and the evaporator of the heat pump. Operational schemes in the UK (Table 1) have been monitored as part of the 'LoCAL' project (European Commission, 2019) and reviewed by Banks et al. (2017) and broadly comprise:

- **Open loop systems** where mine water pumped from a borehole or shaft is used directly in the heat exchanger of the evaporator. After heat exchange, the mine water is usually returned to another part of the underground mine network through a reinjection borehole or shaft. Reinjection is necessary because mine water can be polluted with metals, but where it meets the local regulations for groundwater quality it might be possible to dispose to surface or to active treatment schemes (e.g. Caphouse Colliery, see Burnside et al., 2016a)
- **Closed loop systems** where a heat transfer fluid (usually water with anti-freeze) is circulated in a loop of polythene pipe or a steel radiator placed in a flooded mine shaft or gallery prior to heat exchange at the evaporator. At sites where active treatment of mine water is taking place for environmental reasons, the closed loop pipes or radiators can be placed in the surface treatment ponds.
- **Standing column systems** where mine water is abstracted from depth in a single borehole and, after heat exchange, is returned to the same borehole at a shallower depth (e.g. Athresh et al., 2015; Burnside et al., 2016b). To improve efficiency, standing column wells usually 'bleed to waste' a portion of the mine water after heat exchange. This induces some groundwater flow within the mine network, bringing warmer mine water to the borehole.
- **Gravity driven mine water discharges** could be used to recover mine water heat without the requirement of drilling. However at the time of writing there are no operational schemes of this nature in the UK.

Which heat exchange option to install is project dependent. An important factor that can influence the choice between open or closed loop is whether the mine water is contaminated with dissolved metals, especially iron. This occurs because many coal seams contain significant quantities of pyrite (FeS_2), which oxidises when in contact with circulating water and oxygen during the life of the mine and then goes into solution when the mine floods. If this contaminated water comes into contact with oxygen, the iron can precipitate out as ochre (Banks et al., 2009; 2017). If unchecked, the ochre would rapidly clog the heat exchanger of the evaporator. Hence, for an open loop system fed from contaminated mine water, there will need to be either filters to remove the ochre prior to heat exchange (and these will need to be cleaned or changed regularly) or the mine water must be prevented from coming into contact with the atmosphere. However, this problem does not arise with closed loop where the polythene pipes or radiators are placed beneath the water table within the mine system.

A dedicated 'Geo Observatory' is being built in Glasgow, Scotland (Monaghan, 2019) as part of the UKGEOS project (www.ukgeos.ac.uk). Boreholes drilled into abandoned coal mine workings will be instrumented and data will supplement existing geological models, with the aim of helping to de-risk heat recovery and storage in the UKs disused coalfields.

Table 1: Operational coal mine water heating schemes in the UK.

Location	Type	Borehole depth (m)	Pump depth (m)	Installation year	Heat pump capacity (kW)	Reference
Shettleston	Open Loop	100	n/a	1999-2000	65	Banks et al 2009
Lumphinnans	Open Loop	172	n/a	1999-2000	65	Banks et al 2009
Dawdon	Open Loop	533	103	2011	12	Bailey et al 2013
Markham	Standing Column	490	235	2012	20	Athresh et al 2015/ Burnside et al 2016b
Crynant	Open Loop	65	c.60	2014	35	Farr et al 2016
Caphouse	Open Loop disposed to treatment lagoon	197	170	2015	10	Burnside et al 2016a / Banks 2017
Caphouse	Closed Loop in a mine water aeration pond	n/a	n/a	2015	10	Burnside et al 2016a

6. CONVENTIONAL OPEN LOOP COMPARED TO THERMAL MINE WATERS

It is interesting to consider the potential thermal capacity between an open loop, aquifer based GSHP and a mine water fed GSHP. If the temperature drop across a heat pump is ΔT, then the heat available from extracted groundwater flowing at y L s^{-1} is

$$4180\ \Delta T y \text{ Watts (W)},$$

where 4180 is the volumetric heat capacity of water in J K^{-1} L^{-1} (Banks, 2012). An open loop borehole extracting groundwater at 3 L s^{-1} at 11°C and discharging at 6°C (a 5°C drop across the heat pump) will produce 63 kW of heat, which with a heat pump with a CoP (Coefficient of Performance) of 4 is a total heat output of 84 kW. The mining is likely to have created enhanced permeability from the connected roadways, shafts and adits resulting in an enhanced groundwater abstraction of, say, 10 L s^{-1}. Assuming a slightly higher groundwater temperature arising from the connected mine network of 14°C and discharging at 9°C (also a 5°C drop across the heat pump), produces a thermal output from the borehole of 209 kW. With a heat pump of CoP of 4, results in a total heat output of 279 kW, a greater than 300% increase over the open loop groundwater heat pump system. The CoP of a heat pump increases with increasing input water temperature (Ramos et al., 2015) and so the CoP of the mine water heat pump would likely be greater than 4, requiring less electrical input.

7. DEVELOPING A THERMAL MINE WATER SCHEME

After identifying a user demand and potential customer for renewable heat there are a number of steps to follow to ascertain if mine water heat might be suitable and then be exploited. These are discussed by Harnmeijer and Schlicke (2016), Harnmeijer et al. (2017) and Banks et al. (2017) and are summarized below:

- The extent of mine workings beneath or adjacent to potential customers needs to be ascertained from mine abandonment plans. If a large heating scheme is planned it may include a heat distribution network which can connect the mine workings to the buildings to be heated.
- For large heating schemes it will be necessary to build a 3D model of the disused mines, showing the interconnections between the shafts, underground tunnels and the workings. From the model an assessment can be made of the thermal resource and the likely flow rate of mine water from abstraction boreholes or natural drainage.
- For an open loop system, an understanding of the hydrogeology of the mine system will be needed for designing the location and depth of abstraction boreholes. Ideally, when large volumes of mine water are required, the abstraction boreholes should target open roadways. Figure 4 shows recent exploratory drilling into coal workings in the South Wales Coalfield. A consideration of depth is also required as pumping from depth will incur greater pumping costs, but may access warmer water which will also increase the CoP of the system. The thermally spent water will often be disposed through reinjection boreholes. These should also target open roadways, but must be located such that the returned cooled water does not migrate

rapidly to the abstraction borehole, creating thermal breakthrough. Alternatively, if the mine water is uncontaminated or linked to an environmental treatment scheme, it may be possible to discharge to surface drainage or treatment ponds.

- As has already been mentioned it will be necessary to determine the mine water chemistry in order to avoid problems with clogging, scaling or corrosion and for assessing disposal options for thermally spent water in open loop systems. Water chemistry data may already be available for some locations, but if not a sampling and analysis programme will have to be undertaken.
- An analysis of risks will be required for business, technical and regulatory authority requirements. Examples of risks are;
    - The water yields from boreholes or the temperatures of the mine waters are less than anticipated with time, reducing the cost effectiveness of the scheme.
    - Problems are encountered during drilling of the boreholes, possibly from intersecting unexpected mine voids, encountering artesian conditions, risk of induced subsidence, corrosive mine waters or presence of methane and other gases.



Figure 4: Exploratory drilling as part of a feasibility study for a mine water district heating scheme targeting workings 200-230 mbgl (metres below ground level). Terraced houses are typical of many coalfield areas. Re-profiled coal tips, with flat tops can be seen in the background. September 2017. © British Geological Survey.

8. LICENCING AND PERMITTING

The UK comprises 4 countries and although broadly speaking the licensing and permitting regimes are similar, there can be regional differences. It is beyond the scope of this short review to discuss these in detail so a broad overview is provided.

Permissions are required from both The Coal Authority, and the relevant environmental regulator (for example The Environment Agency in England) for open loop heat recovery and storage systems in coalfields. Interestingly closed loop systems would only require permission from The Coal Authority, and not the environmental regulator, as there is no physical pumping or discharge of mine water. Applications are made simultaneously, however they are often dealt with separately by The Coal Authority and the environmental regulator. This can result in contradictory advice for a single scheme and also the doubling up of work. A simple solution being tested in Scotland is to have a 'one stop shop' for licensing and permitting. Although in its early stages this is a positive step towards addressing and streamlining the regulatory regimes and has potential to be applied across the UK.

The Coal Authority require a 'Heat Access Agreement' and 'Permission to drill in a coalfield' whilst the environmental regulator require 'Permission to pump test a borehole', followed by an 'abstraction license'. Depending on the volume, an abstraction license may not be required. An Environmental Permit is then required for the return of the water to the system. This is a separate application to the environmental regulator and may often not be considered in conjunction with the abstraction license. There is a need to combine the applications and have them considered as 'one system' rather than two separate activities.

Permitting and licensing statutory response times can be at least four months, however in reality may take many more months or up to a year if further information is required. This time frame is likely disruptive to investors and developers and it would be beneficial to reduce the times to encourage development of low enthalpy heat recovery and storage in coalfields.

9. CONCLUSIONS

It is clear that the legacy of hundreds of years of coal mining has left the UK with a thermal resource that is potentially very large and is often located close to urban populations. Abandoned flooded coal mines offer a real potential for low enthalpy heat recovery

and storage in the UK. Competition is also low for mine water as it has little use for potable or industrial water supply. However the geothermal industry in the UK is poorly developed compared to that of many of its European neighbours. Regional and local studies have provided initial estimates of heat recovery and storage, however better data is required to address the known heterogeneity of temperature gradients in many coalfields, which have been shown to range by up to 20°C at similar depths across the UK. Several small proof of concept schemes and small networks are in operation. If the UK is to sustainably utilize these resources, challenges including the permitting and regulation of heat, mapping and quantification of the resources and understanding of the drivers of heterogeneity in mine water temperatures need to be addressed.

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REFERENCES

Abesser, C., Schofield, D., Busby, J. and Bonsor, H. 2018. Who Owns (Geothermal) Heat? Policy Position Paper, British Geological Survey. https://www.bgs.ac.uk/downloads/start.cfm?id=3463

Athresh, A.P., Al-Habaibeh and Parker, K. 2015. Innovative approach for heating of buildings using water from a flooded coal mine through an open loop based single shaft GSHP system. Clean, efficient and affordable energy for a sustainable future: The 7th International conference on Applied Energy (ICAE2015). *Energy Procedia*., **75**, 1221-1228.

Bailey, M.T., Moorhouse, A.M.L. and Watson, I. 2013. Heat extraction from hypersaline mine water at the Dawdon water treatment site. *In* Mine Closure, A.B., Fourie, M., Tibbett, (Eds), Australian Centre for Geomechanics, Perth.

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

Banks, D. 2012. An Introduction to Thermogeology: Ground Source Heating and Cooling, 2nd edn., Wiley–Blackwell, Chichester/Oxford/Iowa.

Banks, D., Fraga Pumar, A. and Watson, I. 2009. The operational performance of Scottish minewater-based ground source heat pump systems. *Quarterly Journal of Engineering Geology and Hydrogeology*, **42**, 347-357. DOI 10.1144/1470-9236/08-081

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

BEIS. 2017.The Clean Growth Strategy – Leading the Way to a Low Carbon Future. Department for Business Energy and Industrial Strategy London. https://www.gov.uk/government/publications/clean-growth-strategy.

British Geological Survey (BGS). 2010. Coal. Minerals UK Fact Sheet. March 2010. https://www.bgs.ac.uk/downloads/start.cfm?id=1404

Burnside, N. , Banks, D. and Boyce, A. 2016a. Sustainability of thermal energy production at the flooded mine workings of the former Caphouse Colliery, Yorkshire, United Kingdom. *International Journal of Coal Geology*, **164**, 85-91. (doi:10.1016/j.coal.2016.03.006)

Burnside, N., Banks, D., Boyce, A.J. and Athresh, A. 2016b. Hydrochemistry and stable isotopes as tools for understanding the sustainability of minewater geothermal energy production from a 'standing column' heat pump system: Markham Colliery, Bolsover, Derbyshire, UK. *International Journal of Coal Geology*, **165**, 223-230 (doi.org/10.1016/j.coal.2016.08.021)

Busby, J., Kingdon, A. and Williams, J. 2011. The measured shallow temperature field in Britain. *Quarterly Journal of Engineering Geology and Hydrogeology*, **44**, 373-387.

The Coal Authority, 2019. Sustainable communities abandoned mine workshop Wales. Jeremy Crooks, Head of Innovation [presentation given in Cardiff, UK May 9th 2019]

Curtis, R., Busby, J., Law, R. and Adams, C. 2019. Geothermal energy use, country update for United Kingdom. European Geothermal Congress 2019 Den Haag, The Netherlands, 11-14 June 2019, 9pp.

European Commission, 2019. Low Carbon After Life: sustainable use of flooded coal mine voids as a thermal energy source – a baseline activity for minimising post-closure environmental risks (LoCAL). Final Report pp108. EUR 29544 en. https://publications.europa.eu/en/publication-detail/-/publication/2a348f71-4479-11e9-a8ed-01aa75ed71a1/language-en/format-PDF/source-897030

Everett., 1882. Fifteenth Report of the Committee appointed for the purpose of investigating the rate of increase of underground temperature downwards in various localities of dry land and under water. Report of the 52nd Meeting of the British Association for the Advancement of Science, 1883, p72 to 74. (https://archive.org/details/reportofbritisha83brit/page/n155)

Farr, G., Sivachidambaram, S., Manju, Watson, I.A., Thomas, H.R. and Tucker, D. 2016. Low enthalpy heat recovery potential from coal mine discharges in the South Wales Coalfield. *International Journal of Coal Geology*, **164**, 92-103.

Graham, J.I. 1921-22. Rock temperatures in the coal-measures of Great Britain (Fourth report to the committee on ‘’The control of atmospheric conditions in hot and deep mines’’. Transactions of the . Institute of M.E.T., 1921-22, vol LXII pp 343-399

Gillespie, M.R., Crane, E.J. and Barron, H.F. 2013. Study into the Potential for Deep Geothermal Energy in Scotland: Volume 2. *British Geological Survey Commissioned Report,* CR/12/131 Scottish Government Project Number AEC/001/11. ISBN: 9781782569862 (web only publication)

Harnmeijer, J. and Schlicke, A. (Eds.). 2016. Feasibility Report of Fortissat Community Minewater Geothermal Energy District Heating Network (Scottish Government, March 2016), ISBN: 978-1-78652-131-6. Available at http://www.gov.scot/Resource/0049/00497924.pdf

Harnmeijer, J., Schlicke, A., Barron, H., Banks, D., Townsend, D., Steen, P., Nikolakopoulou, V., Lu, H. and Zhengao, C. 2017. Fortissat minewater geothermal district heating project: case study. *Engineering and Technology Reference*, 2017, pp. 1-8. (doi:10.1049/etr.2016.0087)

Hall, A., Scott., J. A. and Shang, H. 2011. Geothermal energy recovery from underground mines. *Renewable & Sustainable Energy Reviews*, **15**, 916–924.

Jones, T.D. 1924. The strata temperatures of the south Wales and Pembrokeshire coalfields. *Proceedings of the South Wales institute of Engineers*, **XXXIX**, 559-579.

Jones, T.D. 1926. Further investigation of strata temperature in the south Wales coalfields. *Proceedings of the South Wales institute of Engineers*, **39**, No4, 157-169 XLI

Jones, N.S., Holloway, S., Creedy, D.P., Garner, K., Smith, N.J.P., Browne, M.A.E. and Durucan, S. 2004. UK Coal Resource for New Exploitation Technologies. Final Report. *British Geological Survey* Commissioned Report CR/04/015N.

Lebour, G.A. 1881. On the present state of our knowledge of underground temperatures, with special reference to the nature of the experiments still required in order to improve that knowledge. Transactions of the North of England Institute of Mining and Mechanical Engineers. Vol XXXI. 1881-1882, 59 – 73.

Monaghan, A. 2019. How things change – a UK Geoenergy Observatory in Glasgow. The Edinburgh Geologist. Magazine of the Edinburgh Geological Society. No 65. Spring 2019, 20-25.

Prestwich, J. 1887. On underground temperature; with observations on the conductivity of rocks; on the thermal effects of saturation and imbibition; and on a special source of heat in mountain ranges. Proceedings of the Royal Society of London, **41**, 1-116.

Ramos, E.P., Breede, K. and Falcone, G. 2015. Geothermal heat recovery from abandoned mines: a systematic review of projects implemented worldwide and a methodology for screening new projects. *Environmental Earth Sciences* **73**, 6783-95. doi: 10.1007/s12665-015-4285-y

Spring Statement 2019. https://www.gov.uk/government/news/spring-statement-2019-what-you-need-to-know.

Verhoeven, R., Willems, E., Harcouët-Menou, V., De Boever, E., Hiddes, L., Op ’t Veld, P. and Demollin. E. 2014. 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**, 58–67.

Watson, S.D., Lomas, K.J. and Buswell, R.A. 2019. Decarbonising domestic heating: What is the peak GB demand? *Energy Policy*, **126**, 533-544. https://doi.org/10.1016/j.enpol.2018.11.001

Wiltshire, R. and Burzynski, R. 2008. A high-level study into mine water potential. Presentation at Minewater08, Aachen-Heerlen, 1–2 October 2008.