Low enthalpy heat recovery potential from coal mine discharges in the South Wales Coalfield

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Abstract

Fossil fuels generate the majority of space heating and hot water demand in the UK, contributing to greenhouse gas emissions and energy security issues. Concerns about the long term availability of traditional fossil fuels are recognised by the UK government and sustainable, low carbon supplies are being actively investigated. One such option in the renewable energy mix is the use of low enthalpy heat, using open loop ground source technology to recover heat from abandoned flooded coal mines. To assess this potential in the South Wales Coalfield we measured annual temperatures and chemistry at sixteen mine water sites. Mean monthly temperatures ranged from 10.3 to 18.6 °C with an overall mean of 13.3 °C, proving their suitability for low enthalpy heat recovery. Collated data shows the geothermal gradient can vary within the South Wales Coalfield. Exothermic chemical reactions within abandoned mine workings can also contribute to the overall temperature of mine waters. Using discharge and temperature data we estimate that 42 MW of potential heating energy could be generated from currently monitored mine water discharges, however historic dewatering data from operational mines suggests that 72 MW could be generated, enough to heat about 6500 homes. The true potential, if new pumping wells were drilled to exploit flooded workings is likely to be much greater. The use of low enthalpy mine water for space heating and hot water indicate a total emission reduction of around 59% and 76% compare to main gas and electricity heating respectively.

Keywords:

Ground source heating, mine water, South Wales, abandoned mines.

1. Introduction

1.1 The space and hot water heating problem

The consumption of energy for domestic and commercial heating and hot water requirements contributes to almost half of the UK's energy usage (DECC, 2013), costing the UK economy nearly £33 billion per year (DECC, 2012). The principal source of energy for heating and hot water in the UK is natural gas, a fossil fuel, which supplies 70-80% of the heating demand (DECC, 2013) but also contributes around a third to the UK's greenhouse gas emissions (DECC, 2012). The UK Government is targeting renewables to provide the equivalent of 12% of the heating demand by 2020 (DECC, 2009) whilst also reducing greenhouse gas emissions.

Currently renewable heat systems only account for around 1% of the heat generated in the UK, falling short of the government's target of 12% (Conner et al., 2015). The UK Government recognises that the current use of fossil fuels is not sustainable, and that there is a growing need for both energy security and a reduction in carbon emissions (DECC, 2009). One option for generating sustainable low carbon heating and hot water is the use of heat exchangers to exploit mine water associated with flooded workings. Mine waters could provide a sustainable, low enthalpy heating source to supplement the renewable energy mix in the UK, whilst also improving energy security. Abandoned and flooded mines also have the potential to be used for the storage of energy, including compressed air energy systems or the direct use of mine water to regulate the temperature of microalgae to obtain on-site biodiesel production (Scott et al 2009; Shang et al 2010). Compressed air energy storage is commonly used where there are large voids, such as salt mines and limestone caverns (Evans, 2009). Other potential heat uses include agricultural glasshouse heating, produce drying and fish farm heating.

There is a substantial, unused resource of mine water in the UK. The Coal Authority estimates that it pumps in excess of 3,000 l of mine water every second from abandoned mine workings across the UK, estimating that there is 100 MW of potential heat energy (Coal Authority, 2010); despite this the UK has been slow to adapt to this technology (Bailey et al., 2013). To better characterise the low enthalpy heat recovery potential of flooded workings in South Wales, and to help support the development of this low enthalpy heat extraction, we collated information on mine water temperatures, discharge rates and measured geothermal gradients within the South Wales Coalfield. Raferty (2000) and Banks et.al (2009) reported the importance of geochemistry in the context of mine water based heat pump system. In order to run the heat pump system smoothly and avoid aquifer contamination, mine water chemical composition baseline studies, monitoring and study of mineral stability are necessary.

The data was used to;

1. characterise annual temperature variation of mine water discharges
2. estimate the possible contribution of exothermic chemical reactions to mine water temperature and geochemical facies of mine water in South Wales Coalfield.
3. describe measured geothermal gradients
4. estimate the heat potential from mine water discharges in the South Wales Coalfield

1.2 Existing mine water heating systems

Abandoned flooded mine workings can provide heating and cooling for a single household or for district heating. Low enthalpy energy contained within mine water is exploited using heat pumps. Different types, designs, and configurations of heat pumps are available, enabling them to meet either the total heating requirement of a building, part of the load, or to cover the basic requirement while a conventional system supplies the peaks. There are two basic types of heat pump systems:

Open-loop systems: Groundwater is pumped from a borehole (or mine shaft) and circulated directly through the heat pump, which extracts heat directly from the water. This method is appropriate where a significant water yield of suitable quality, can be sustainably abstracted.

Closed-loop systems: Groundwater is not abstracted however a liquid coolant is pumped to depth via a pipe network in a borehole to capture the heat from the mine water. The coolant is never in contact with the mine water and thus the closed-loop configuration can be used where contamination is an issue or where flooded workings cannot be intercepted. The limiting factor of these closed-loop systems is the surface area of the heat exchanger, which is dependent on the cross sectional area of the linear component of the heat exchanger and its length.

The use of mine water for heat recovery has been successfully demonstrated (Banks et al., 2009; Jessop et al., 1995, Watzlaf and Ackman, 2006; Wieber and Pohl, 2008; Verhoeven et al., 2013). Mine water heating systems have been in operation since the early 1980s in mining areas in the USA and Europe (Table 1) illustrate the potential for low enthalpy heat recovery from abandoned mine workings. The installations vary in size, from single buildings (Hall et al., 2011) to larger district heating and cooling systems (e.g. Verhoeven et al., 2013). The municipality of Czeladz, Poland is located in the Central European Coalfield where there is considered to be a large potential for the utilization of geothermal energy from mine waters (Malolepszy, Ostaficzuk 1999). It is estimated that the potential thermal output from abandoned mine water is 2.5 MWt and a small scale pilot project in Czeladź is in operation generating 117 kW (REMINING-Lowex, 2012). The potential value of mine water associated with the flooded Barredo and Figaredo mine workings, near Mieres in Central Asturias in Spain, implies there is potentially 40 million m^3 per year of available mine water that could provide 260,000 thermal MWh per year (Jardo ´n et al 2013). Currently a heat pump of 117 kW capacity provides heating to a research building using mine water from the Barredo Shaft and there are plans to heat other buildings using same source. One of the most successful mine water schemes is in the municipality of Heerlen, Netherlands, where a low-temperature district heating system has been in operation since October 2008, funded by the European Interreg IIIB NWE programme and the 6th Framework Program project EC-REMINING-lowex. The mine water project has been upgraded from a straight forward pilot system to a full-scale hybrid sustainable energy structure called Minewater 2.0 (Verhoeven et al 2014).

In the UK this technology was first introduced in Scotland when a temporary pilot site was constructed at Mossend in 1992 followed by two permanent sites commissioned in 1999-2000 at Shettleston and Cowdenbeath (Banks et al., 2009). Recently the Coal Authority has installed a demonstration system in Dawdon, County Durham, UK generating an estimated 12 kW heat output (Bailey et al., 2013). Despite having a long mining history and extensive abandoned flooded mine workings, there has been very little use of mine water for ground source heating in South Wales. The National Assembly for Wales commissioned a desk based feasibility study for potential heat extraction from the South Wales Coalfield (White, 2007) concluding there was a viable source for heating whilst also converting an '*environmental liability in to an environmental asset'*. A feasibility study near the Taff Merthyr mine water treatment works (Manju et al., 2011) suggested that 220 kW could be produced to heat a nearby sports centre, however, funding for this project did not materialise.

To date, there is only one operational mine water heat pump system in Wales, located in Crynant in the Dulais Valley, South Wales, UK National Grid Reference SN 79338 04293. Installed in 2014 as a proof of concept during the European Regional Development Fund supported ‘Seren Project’ the open loop scheme abstracts mine water at ~11.5 °C from flooded workings from the Carboniferous Coal Measures strata, Rhondda No 2 seam at a depth of 65 m producing 35 kW of heat and hot water demand for a large farmhouse, workshops and adjoining physiotherapy centre.

1.3 Social, environmental and regulatory issues associated with mine water heating systems

The use of mine water as a renewable heating source could contribute to the sustainable regeneration of former mining areas, providing both jobs and secure, low carbon heating energy. Flooded mine workings are attractive as they have increased permeability’s and storage, stable year round temperatures at depth, lack of competition from other groundwater users and are often located near urban areas (Younger, 2014). Other benefits include the potential to convert a present day environmental liability (Environment Agency, 2008) into an environmental and economic asset generating both a reduction in greenhouse gases (Preene and Younger, 2014) and financial income (Bailey et al., 2013).

There are operational, environmental and regulatory risks and issues associated with the use of mine water. Operational problems includes concerns of clogging and corrosion of systems from the precipitation of ferric hydroxide (Bailey et al., 2013; Younger, 2014). Precipitation of ferric hydroxide can be minimised by excluding interaction of mine water with the atmosphere within the heat exchanger (Banks et al., 2009). Scaling can be caused by carbonates due to pressure and temperature differences. However, the likely low pH value of the mine water would restrict scaling problem. Maintenance points could be installed so that cleaning devices can be pumped through the pipes to counter the scaling problems. There is also a perceived risk of explosive gasses and collapse of workings (Younger, 2014; Preene and Younger, 2014).

In South Wales, UK the Coal Authority and the environmental regulator, Natural Resources Wales (NRW) control and manage the sustainable use of mine water for heating and cooling purposes via their regulatory regimes. The Coal Authority require a ’Mine water Heat

Recovery Access Agreement' whist NRW may require an abstraction licence and permit or exemption to discharge back into the workings.

2 Geology and hydrogeology

The South Wales Coalfield extends approximately 90 km from Blaenavon in the east to Kidwelly in the west and 27 km from north to south covering an area of approximately 2,690 km^2 (Thomas, 1974) (Figure 1). The coalfield, which incorporates strata from the Carboniferous period, forms an east-west trending syncline within which are many smaller anticlines and synclines, trending ENE-SWS. Major disturbances including the Tawe and Neath Valleys trend NE-SW, but the main fault pattern is NW-SE and WNW-ESE (Thomas, 1974). Coal mining in the South Wales valleys declined steadily after the general strike of 1926 with significant closures of coal mines in the 1980's and 1990's (Robins et al., 2008). Following closure, as mine de-watering ceased, water levels rebounded, flooding many mine workings. As mine water levels rebounded, new gravity fed discharges occurred (Robins et al., 2008) and to mitigate against impacts on the surface water environment the Coal Authority installed mine water treatment systems (Younger et al., 2004).

The hydrogeology of the South Wales Coalfield was first described by Ineson (1967) who characterised mine water chemistry. A study of the hydrology of the Carboniferous Pennant Measures was produced following the Aberfan disaster (Gray, 1969) and Rae (1978) considered the potential for mine water for use in public water supply. Following the 1970's fuel crisis Thomas et al. (1983) investigated the deep geothermal potential in South Wales, concluding the western, deeper part of the coalfield to be most attractive for deep geothermal systems where water near 60 °C could be obtained. The problems of achieving adequate water flow from depths of 1500-2000 m were recognised; however, the possibility of low enthalpy heat from flooded shallow workings was not considered. Lewis et al. (2000) delineated hydraulic connections between mine workings, defining 13 'mine water ponds' across the South Wales Coalfield (Figure 1). These 'ponds' roughly correlate with the topographical surface water boundaries of the major river systems suggesting a catchment and sub catchment topographical control on flow, with limited deep or cross catchment flow, a hypothesis also favoured by Robins et al., (2008) who produced a 3D geological model utilising it to better understand mine water flow within the coalfield.

The occurrence of disused flooded mine workings will produce highly permeability pathways and increased localised storage, far greater than would have occurred in natural pre-mining conditions. The vertical and lateral interconnection of mine workings to surface features such as drains, shafts and small streams offers the potential for rapid direct recharge. The interconnection of mine workings may allow water to flow across previously existing natural hydraulic barriers although the coalfield is thought to be constrained generally within topographical catchments (e.g. Lewis et al., 2000; Robins et al., 2008). Recharge pathways to mine workings, and interception of local surface water drainage can allow a rapid response to precipitation events, and is reflected in measured flows at gravity driven adits, between 84 to 232 L/s at Abersychan and 40 to 102 L/s at Cefn Hengoed (Figure 1). The majority of mine discharges are gravity driven in the South Wales Coalfield (Robins et al., 2008), however, some sites employ transfer pumps to move water from the location of the gravity driven discharge to a nearby higher elevation treatment facility. There is only one actively pumped site in South Wales at ‘Six Bells’ (Vivian Colliery) where mine water is abstracted from an abandoned flooded mine at a depth of 217 m before being pumped to settlement ponds and treatment wetlands.

3 Material and methods

3.1 Monitoring network design

The Coal Authority monitors mine water flow and chemistry at 89 abandoned collieries in South Wales. The monitoring locations were selected from this existing network as all had baseline flow, chemical and temperature data and safe access. The monitoring sites (Figure 1) are named after their location and are not named after the collieries that they drain. The lack of access to deep boreholes within the study area favours the monitoring of gravity driven discharges, the range of monitoring sites are presented in a simplified conceptual model (Figure 2) and comprise of gravity driven adits (A) or adits where a transfer pump is used to lift the water a short distance to a local treatment facility (TP); also included are a single pumped borehole (P) and an un-pumped mine shaft (S). Spatial analysis against a list of criteria allowed selection of 16 monitoring sites (Figure 1). The site selection criteria included consideration of the following: proximity to urban areas with preference to sites within 500m, proximity to Local Development Plan areas within 500mand the availability of baseline temperature, chemistry and discharge data.

3.2 Temperature

Hobo Pro V2 –U22-001 Water Temperature sensors, were installed at sixteen sites including; two shafts (S), seven gravity driven adits (A), one pumped shaft (P) and six sites where pumps transfer water from adits to treatment facilities at higher elevations (TP). Temperature was recorded every 30 minutes, with an accuracy of ±0.21°C from 0° to 50°C and a resolution 0.02°C at 25°C as reported by the manufacturer. During installation and every four months thereafter, field temperature measurements we checked the calibration of the in situ temperature sensors, using an Omega HH501DK Type K Thermometer with an accuracy of ±0.3°C. The temperature sensors were submerged in flowing mine water as close to the discharge as safely possible. Where shafts were monitored (Abercwmboi and Tower Colliery) the depth of the logger was recorded. Where the velocity of mine water discharge was significant the temperature sensors were secured within a 1m section of pipe slotted along its length and covered with a geo-membrane, attached to a concrete wall or weir.

To characterise the range of geothermal gradients in the South Wales Coalfield existing temperature data were collated from, Burley and Gale (1981); Busby et al., (2011), the British Geological Surveys 'Geothermal Catalogue' and 'RECALL' database. Twenty two boreholes, comprising primarily of exploratory boreholes associated with coal mining, rather than boreholes drilled specifically for geothermal exploration. BGS Borehole reference numbers are: SN50NW/007, SN50NW/008, SN50NW/009, SN50NW/010, SN50NW/012, SN50NW/013, SN50NW/021, SN50NW/022, SN50NW/025, SN50NW/028, SN60NE, SN60NE/006, SN88NE/033, SN88NE/035, SS88NW/021, SS88NW/022, SS88NW/020, ST08SE, ST18NW/004, SN60NE/019 and SSNE/059. Estimated temperatures were based on the nearest measured temperature in each borehole at the following depths; 100 m, 200 m, 500 m and 1000 m below ground level, following the same approach as Busby et al., (2011). The data represent in situ profiles from a number of deep boreholes, however there is uncertainty as to the timing of the data collection post drilling, the effect of circulation of water within the boreholes and the influence of intercepted mine working, all of which are factors which could influence the measured temperatures, from the natural geothermal gradient in undisturbed bedrock.

3.3 Mine water chemistry

The water quality parameters such as pH, electrical conductivity (EC), oxidation reduction potential (ORP) and dissolved oxygen (DO) were measured using an In-Situ Inc. SmarTROLL™ multiparameter instrument attached to a flow through cell. A WaSP P3 submersible pump was used to pump the water into a flow through cell, directly from the outflow, limiting interaction of mine water with the atmosphere, until stabilised values for pH, temperature, electrical conductivity and redox were achieved. Field alkalinity was performed using a Hanna Instruments field alkalinity kit. Three separate aliquots of water samples were collected as follows:

- Sample 1:The water samples, filtered through 0.22 µm were collected and acidified to ≤ pH 2 using concentrated HNO_3/HCl for cation analysis.
- Sample 2: An unfiltered water sample was acidified using Concentrated HCl to determine the total iron content.
- Sample 3: A filtered aliquot of water samples were collected for major anion analysis (fluoride, chloride, sulphate and nitrate).

The iron precipitate deposited on the filter medium was digested and dissolved using a known volume of HCl to determine suspended iron. The mineralogical identification was carried out using a Phillips X-ray diffractometer on an iron oxide sludge collected from Six Bells mine water treatment settlement pond. The powder X-ray diffraction (XRD) pattern was analysed using Phillips Xpert HighScore computer application with JCPDS (Joint Committee on Powder Diffraction Standards) data base. The major cation and trace ions analyses were performed using a Perkin Elmer Optima 2000 inductively coupled plasma optical emission spectrometer (ICP-OES).The anion analyses were performed using a Dionex IC2000 ion chromatography configured with hydroxyl based anion retention column. Since there were no substantial changes in the ion concentrations in the mine water during the monitoring period, the data presented in the present study are the mean values of three water sampling results carried out in between July 2013 to October 2014. The water sampling and analysis were carried out according to the procedures described in the Standard Methods for the Examination of Water and Wastewater (American Public Health Association, 1999) and the hydrochemical analysis were performed using Geochemist's Workbench Student edition (www.gwb.com).

4 Results and discussion

4.1 Mine water temperatures

Temperature data are displayed on a box and whisker plot (Figure 3) which are used to show variation within a dataset. In this example we have plotted both the median and mean lines within the main box. The upper part of the box is the 75th percentile and the bottom of the box is the 25th percentile whilst the 'whiskers' represent the 5th and 95th percentile of the data and statistical outliers are represented. Mean temperatures range from 10.3 ^{o}C (Blaenavon) to 18.6 ^{o}C (Six Bells) with an overall mean of 13.3 ^{o}C. The majority of sites display only small temperature variations during the monitoring period, however variation between the study sites >8 ^{o}C. The lowest mean temperatures are recorded at Blaenavon (10.3 ^{o}C) and Tan y Garn (10.9 ^{o}C) and may reflect the positioning of the data logger at the inflow to the treatment wetlands, where discharged mine water, under low flow volumes may be influenced by changes in atmospheric temperature. The warmest mean temperature (18.6 ^{o}C) was recorded at Six Bells. Mine water at Six Bells, is the only example of deep pumped mine water in this study and is abstracted from flooded working from a 217 mbgl, limiting interaction with recent recharge or the influence of atmospheric temperatures. Abersychan, Crumlin Navigation are adits and Abercwmboi is a shallow shaft, all three have display large annual temperature variations and this is attributed to mixing of cooler recharge waters. The discharge or flow at Abersychan, ranges from 84 – 230 Ll/s (Coal Authority data) reflecting its use as a combined surface water and mine water adit and explaining the variability in the measured temperature. It was only possible to measure mine water both at depth and in situ at one site, Tower 4, where a logger was installed at 170 mbgl in a disused mine shaft. Mine water is not pumped from this shaft and a mean temperature of 16.5 ^{o}C with little variation, suggesting that at depth, mine water temperatures will be stable throughout the year. 'Penywaun' located 3.5 km to the Southeast of Tower 4 receives drainage from the same catchment, however the mean temperature is much lower (11.7 ^{o}C) and varies more, suggesting periodic mixing with cooler recharge water.

Time series temperature data from a subset of sites are compared to the monthly mean air temperature data (Met Office) for the period of one year (Figure 4) the data period is shorter than that displayed in Figure 3. The sites were chosen to represent the range of monitored temperatures and types of site in this study. Crumlin Navigation is a gravity driven adit, and at the point of monitoring, approximately follows the mean air temperature, possibly reflecting the influence of cooler recharge waters entering the drainage system. Lindsay, Mountain Gate and Tan y Garn are adits with transfer pumps to treatment wetlands, however their temperatures are more stable throughout the year, susceptible only to relatively short lived temperature changes that may reflect localised recharge events, periods of intense rainfall. 'Six Bells' is the only truly pumped site, monitored at the surface at the pumped outflow, it represents water from flooded working 270 mbgl. The time series fluctuates rapidly as the pumping regime is not constant throughout the day, however an overall mean temperature of > 18 ^{o}C is maintained throughout the year. It is the stability of most of the measured mine waters (Figure 3 & 4) that makes them an attractive proposition for ground source heating. Due to paucity of information on the depth and interconnection of mine water flow within abandoned mines in South Wales (e.g. Lewis et al., 2000) it was not possible to correlate recorded mine water temperatures with the maximum depth mine workings.

4.2 Geothermal gradients in the South Wales Coalfield

Characterisation of the geothermal gradient within the coalfield is of use should deep mine water be targeted, such as at Heerlen, Netherlands where mine water is abstracted from a depth of 700m at a temperature of 28°C (Verhoeven et al., 2013). In the UK the average annual groundwater temperature is between 10-11°C (Stuart et al., 2010) at about 15 mbgl, increasing with depth, following the average UK geothermal gradient of 28°C/km, calculated for the upper 1 km of the sedimentary crust (Busby et al., 2011). Applying these UK average figures groundwater at 100 m depth could be predicted to be about 12.8 – 13.8 °C and at 1000m about 38 -39°C. In reality the geothermal gradient varies across the UK, and at depth (>15 mbgl) is influenced by various geological and hydrogeological settings (Busby et al., 2011). The same is true in the South Wales Coalfield, and geothermal gradients, based on data from five deep boreholes (Burley and Gale., 1981) were predicted to range from 20.5 to 27.6°C/km (Thomas et al., 1983). Using the data estimated at 1000 m depth (Figure 5) a range of geothermal gradients from 13.9 to 32.8°C/km averaging 23.9 °C/km can be estimated with temperatures at 1000m depth ranging from 22 °C to 42 °C. This suggests that, although there is significant variation in the measured geothermal gradient across the South Wales Coalfield, there is significant potential for heat recovery if deep flooded mine workings could be intercepted. The temperature range, cost of drilling and potential to achieve a sustainable yield from depth should also be considered in any cost benefit analysis. Caution should be taken when applying the geothermal gradient data presented to predict temperatures of deep mine workings. The boreholes used were not drilled specifically to measure the geothermal gradient, and factors including potential circulation or mixing of groundwater and mine water in boreholes may influence the measurements. Thus the natural geothermal gradient in the South Wales coalfield remains ambiguous. Since the closure of many collieries and the back-filling and capping of deep shafts and boreholes for safety reasons there is now limited access from which to measure contemporary geothermal gradients within the South Wales Coalfield.

4.3 Mine water chemistry

The observed pH values were close to neutral pH, rather than anticipated acidic pH at an acid mine drain. The reason behind this can be explained by the bicarbonate buffering which is produced by alkaline minerals such as calcites. When mines are initially flooded low pH values caused by the pyrite oxidation can induce the dissolution of calcium minerals which buffers the acidity and controls the calcium, iron concentrations and thus pH value of the mine water. This effect has been detailed from a post flooding study on an underground coal mine in Pennsylvania, showing that pH increased in the four years following flooding Donovan et al., (2003). Data from the South Wales Coalfield show that the pH values of the study sites ranged between 6.53 (Ynysarwed) to 7.83 (Crumlin Navigation), however there was little variation at individual sites during the study period. The pH values from the present study are a factor of calcium mineral dissolution and high alkalinity that corresponds to prolonged period of flooding and the availability of mineral calcite which neutralizes the acidity and increases the pH values (Brown et al., 2002). Calcium, sodium and magnesium were the predominant cations in the mine water. The calcium/sulphate($\frac{Ca^{2+}}{Ca^{2+}+SO_4^{2-}} < 0.5$) and magnesium/calcium ($\frac{Mg^{2+}}{Ca^{2+}+Mg^{2+}} < 0.5$) ratio indicates that the most likely source of magnesium and calcium was pyrite oxidation influenced limestone-dolomite dissolution. The calcium/sulphate ratio (< 0.5) and the high bicarbonate concentrations indicates that calcium is removed from the mine water by ion exchange or calcite precipitation (Hounslow, 1995) (Table 2). During the monitoring period, the sampling points showed little variation in cation and anion concentrations with maximum variation of ±5% to the presented values in Table 2. Mine water types plotted on a Piper diagram (Figure 6) and indicate that the dominant water type is Na-HCO_3 followed by Na-SO_4, Ca-SO_4, Mg-SO_4 and Mg-HCO_3. The anion triangle on the right shows that the sulphate (range from 97.5 mg/L to 1119 mg/L) and bicarbonate (range from 165 mg/L to 1555 mg/L) are the predominant anions (Figure 5 and Table 2). The piper diagram further supports previous observations that mine waters were influenced by pyrite oxidation and neutralized by calcite (Hounslow, 1995; Brown et al., 2002). The saturation index (SI) values indicates that the mine waters were almost saturated with $CaCO_3$ which may result in mine water that have a tendency to be corrosive and the implications for heat pump system components and design should be considered (Table 2).

Iron oxides in the mine water samples are either over saturated, where the SI is a positive value, or at apparent equilibrium (SI = 0) where iron will precipitate out as iron oxides. The iron oxide mineral is oversaturated in the mine waters (Table 3) and will precipitate as goethite or ferric hydrite (Figure 7). Aqueous chemistry of manganese and iron are similar. Any soluble manganese and iron will be in reduced state (Mn^{2+} and Fe^{2+}) under the deep mine environment. The redox condition of the mine water influences the soluble iron and manganese concentrations. Despite the high dissolved oxygen and high Eh values measured at the discharge points. There were considerable amounts of dissolved iron concentrations in the mine water which suggests the mine water was undergoing rapid oxidation process. Installation of ground source heat pump systems involves drilling activities which could affect reduced mine water chemistry by changing the redox conditions. Even though the systems are closed, the oxidation process probably occurs at the discharge boreholes, so the iron concentrations, dissolved oxygen and oxidation reduction potential values measured at the discharge points were used in the calculation to simulate the rapid oxidation during the drilling and operation of heat pump system. The pH-Eh diagrams (Figure 8 and 9) indicate the dominant form of Fe and Mn present in the water samples under the given chemical composition of mine water. The Eh-pH diagram is constructed for the average Fe concentration and average temperature (Fe activity = 3×10^{-4} moles/L (17 mg of Fe/L at 14°C). The most predominant phase of Fe was hematite (Fe_2O_3) or goethite (FeOOH) or ferric hydrites. Considering the redox condition at the mine water discharge points, iron will be preferentially oxidized and precipitate out as iron oxides such as goethite, ferrihydrite and amorphous iron hydroxides. The XRD pattern (Figure 7) shows the presence of goethite in the suspended solids is removed from the oxidized mine water samples.

4.4 Exothermic reactions as heat generation in mine water

The majority of geochemical reactions involving minerals and mine water are exothermic. In addition to the depth, the primary driver for the temperature. Determining the energy released from exothermic reactions would exhibit the possible contributions by geochemical reactions. For example; Pyrite oxidation reactions are highly exothermic and are sufficient enough to increase temperatures in flooded mine workings, this is in sulphide mines where pyrite oxidation increases the mine temperature to 35-50°C. The phenomena is also recognised in coal mines (Younger, 2004; Banks et al., 2004). The discharge at Ynysarwed (Figure 1) was used as an example where total iron concentration are 76.85 mg/L (0.001377 mol/L) (Table. 2). The overall pyrite oxidation reactions for dissolving iron can be written as described in equation 1, where, (ΔH_r) is enthalpy of overall reaction in kJ/mol, negative signs indicates that the reactions are exothermic, C_p is molar heat capacity of water and ΔT is the temperature released to the water (Langmuir, 1997 and Atkins and Paula, 2006).

Equation 1

$$\mathrm{FeS}_2 + \frac{7}{2}O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+ \qquad \Delta H_r = -1538.4\ \mathrm{kJ/mol}$$

$$\text{Temperature released to water} = \Delta T = \frac{\Delta H}{C_p} \text{ at constant pressure}$$

$$\Delta T = \frac{-1538400\,\frac{\mathrm{J}}{\mathrm{mol}} \times\ 0.001377\ \frac{mol}{L}}{55.5\,\frac{mol}{L} of\ water \times 75.29\,\frac{\mathrm{J}}{\mathrm{Kmol}}} = -0.507°K\ per\ L\ of\ water$$

Exothermic reactions generated by pyrite oxidation will thus increase the water temperature at Ynysarwed by 0.5°K per L of water. Similarly, the calculated ΔT for Six Bells, Morlais, Lindsay, Glyncastle and Tan Y Garn were 0.1 $°K$, 0.15 $°K$, 0.11 $°K$, Glyn Castle 0.13 $°K$ and 0.37 $°K$.The temperature increase is an approximate estimation for the reaction that assumes that iron will end up in solution and are based on the concentration of iron and sulphate values at the discharge point rather than within the flooded mine workings. Considering the geothermal influence and the mixing of water with different temperatures, the temperature increase by the exothermic reactions are marginal. But the energy released by the geochemical reactions such as iron oxidation/reduction and calcite dissolution may also contribute to mine water temperatures.

4.5 Thermal resource estimate of mine water discharges and potential reduction of CO_2

Estimates of thermal resource can be produced using mean mine water discharge temperatures and known discharge or pumping rates. To estimate the potential energy that can be extracted from mine water discharges the following equation was used;

Equation 2

$$H = Q \times \Delta T \times S_w$$

Where H is the heat energy (W)

Q is the flow rate of water (L/s)

ΔT is the temperature change across the heat exchanger (˚C)

S_w is the volumetric heat capacity of water ($S_w = 4180$ J K^{-1} L^{1})

Mean annual flow rates were calculated from Coal Authority Data (1998 - 2004) with a value of 10 L/s assumed for sites where no data was available. In general, it is thought reasonable to expect a flow of about 10 l/s in mining-enhanced aquifers. The mean annual mine water discharge temperature of 13.4 ˚C was used with a ΔT of 5 ˚C applied across the heat exchanger to calculate available thermal energy. To adhere to environmental regulations the ΔT between the inlet and outlet must be less than 8°C and the outlet temperature must not exceed 25 °C (Environment Agency, 2012). This simplified calculation looked at the potential of mine water in contributing the heat demand of nearby communities as the domestic sector in the UK accounts for over 30% of final energy consumption (DECC, 2012a). Over three quarters (82%) of the energy we use in our homes is for space and hot water heating, most of which is met using gas-fired boilers (81%) currently (DECC 2012b). Cooling accounts for around 0.5% of overall energy demand, but in time this may increase as the UK grows warmer as a result of climate change (DECC 2012b). Table 4 provides the list of monitored locations, with their mean annual discharge flowrate, mean water temperature and their corresponding available thermal energy.

The sum total of thermal energy from the 16 monitored locations shows that circa 15 MW of thermal energy can be extracted from freely discharged mine water based on a 24 hour × 365 days a year pumping regime which could potentially heat up nearly 1362 domestic houses in the nearby community based on average energy consumption of a UK household be 18.6 MWh per annum (Kelly and Thomas, 2012). To know the indicative idea of the possibility of utilising mine water in close proximity to built-up areas within the 500m radius of the monitored location if there is any, number of building was estimated based on available Ordnance Survey information as presented in table 4. Table 4 provides the signal that a few monitored surface discharges are closely matching the building demand to the likely available warm mine water heat source. Such heating schemes can be applied on a neighbourhood scale by way of a district heating network serving the local community typically integrating heat pumps. It is estimated that there is 42 MW of potential thermal energy when estimation was up scaled to include the 62 post closure sites monitored by the Coal Authority in South Wales, where a combined mean discharge is reported to be 2025 L/s (Coal Authority data 1998-2014). 42 MW of potential thermal energy from existing mine water discharges is enough to heat 3848 domestic houses. The range of thermal values calculated represent only the potential heat that could be extracted from mine water discharges and does not estimate thermal potential from possible new abstractions from deeper flooded mine workings, thus the true thermal potential, is likely to be greater than 42 MW. Dewatering data collected from 320 operational mines (Coal Authority Data 1948-1965) suggest a mean discharge of 3444 l/s which has the potential to generate about 72 MW of thermal energy based on constant rate pumping; enough to heat approximately 6500 typical homes.

The potential thermal energy resource can be scaled using a heat pump compressor. Assuming a heat pump coefficient of performance COP = 4, a deliverable thermal energy of 42 MW could be achieved from mine water, applying the following equation:

Equation 3

$$Thermal\ heat\ energy\ delivered = \frac{H \times COP}{(COP - 1)} = 42 \times 1.33 \approx 55.86\ MW$$

only 14 MW of electricity would be required to power the heat pump system. This potential thermal heat energy could also provide considerable environmental benefits including the reducing CO_2 emissions associated with traditional source of heating and energy security. The CO_2 emissions from operating a heat pump are directly linked to the carbon content of the electricity used to power it. When operating in the UK, where 0.381 kg of CO_2 is emitted per kWh of electricity, heat pumps could be expected to produce up to four times less CO_2 than a current heating technology. Based on the SAP 2012 projection for 15 year period (2013-2027) where CO_2 emission is projected to be 0.222 kg of per kWh of main gain and 0.381 kg per kWh of electricity, the production of 55 MW would imply a total emission reduction of around 59 % and 76 % compared to mains gas and electrical heating respectively.

5 Conclusions

There is significant potential for the sustainable use of flooded mine workings in the South Wales Coalfield for heat recovery. Worldwide, flooded mines have been proven to be suitable for the recovery of low enthalpy heat, providing energy security and sustainable low carbon heating. Development of this technology in Wales could reduce CO_2 emissions of around 59% and 76% compare to mains gas and electrical heating respectively. We estimate that 42 MW to 72 MW of heat could be recovered from the South Wales coalfield, enough to the heat about 6500 typical domestic houses. To demonstrate the possibilities a small test site has been installed and produces 35 Kw of heat and hot water demand. In situ monitoring of mine water temperatures across the coalfield indicate that discharge temperatures range from 10.3 to 18.6 ^{o}C (mean of 13.3 ^{o}C). Importantly many sites display relatively stable- year round temperatures suggesting flooded mine working would make ideal targets for the installation of ground source heat pumps. Temperature data up to 1000 m depth was collated however the cost of deep drilling may well favour sustainable use of shallower systems. Available information on the geothermal gradient suggests variable conditions across the coalfield, however caution is exercised as much of the data used is third party associated with exploratory drilling rather than geothermal exploration.   The influence of exothermic reactions, such as pyrite oxidation, to the overall temperature of the mine water is considered to be marginal, contributing between 0.1 and 0.5 $°K$ per litre of water. Design of heating systems needs to consider the chemistry of mine waters and the potential problems relating to precipitates and deposit of iron oxides.

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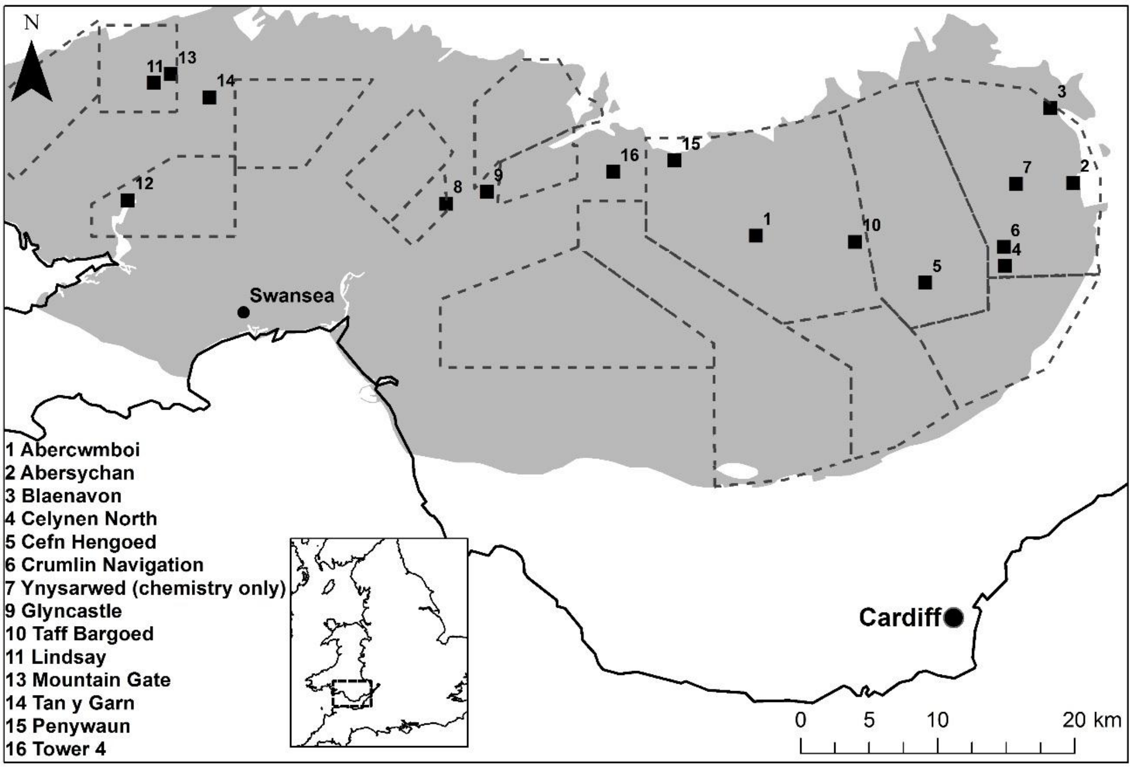

Figure. 1. Location of mine water monitoring points for this project within the South Wales coalfield (grey shaded area). Mine water ‘ponds’ as delineated by Lewis et al., (2000) are represented by grey dashed lines. Contains Ordnance Survey data © Crown Copyright and database rights 2015. Geology from BGS 1:625K DigiMap.

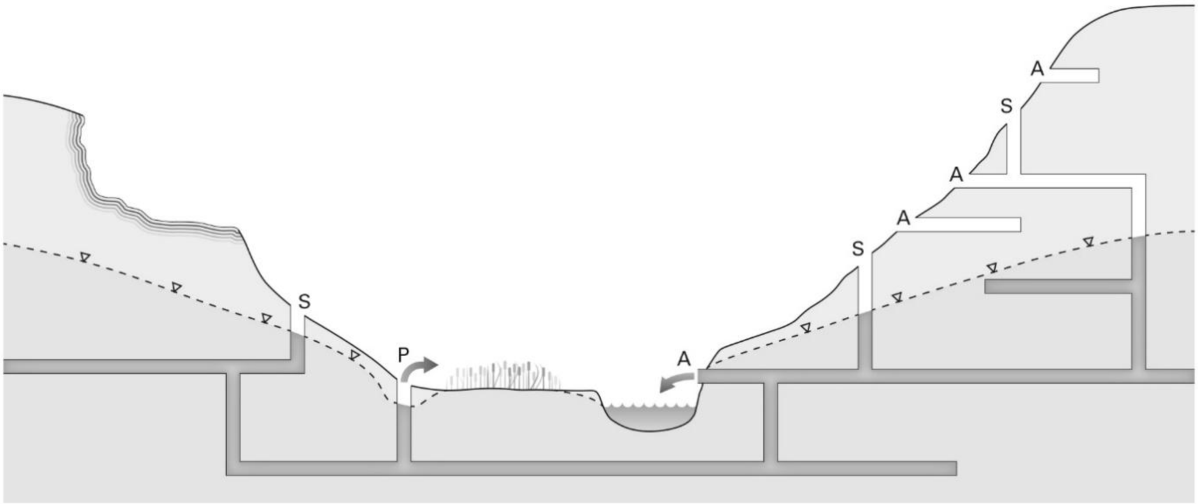

Figure 2. Conceptual diagram showing the types of monitoring locations instrumented with temperatures sensors, including S = non pumped shaft or borehole, A = adit, P= pumped shaft or borehole or could be used to reflect mine water being pumped into a treatment wetland.

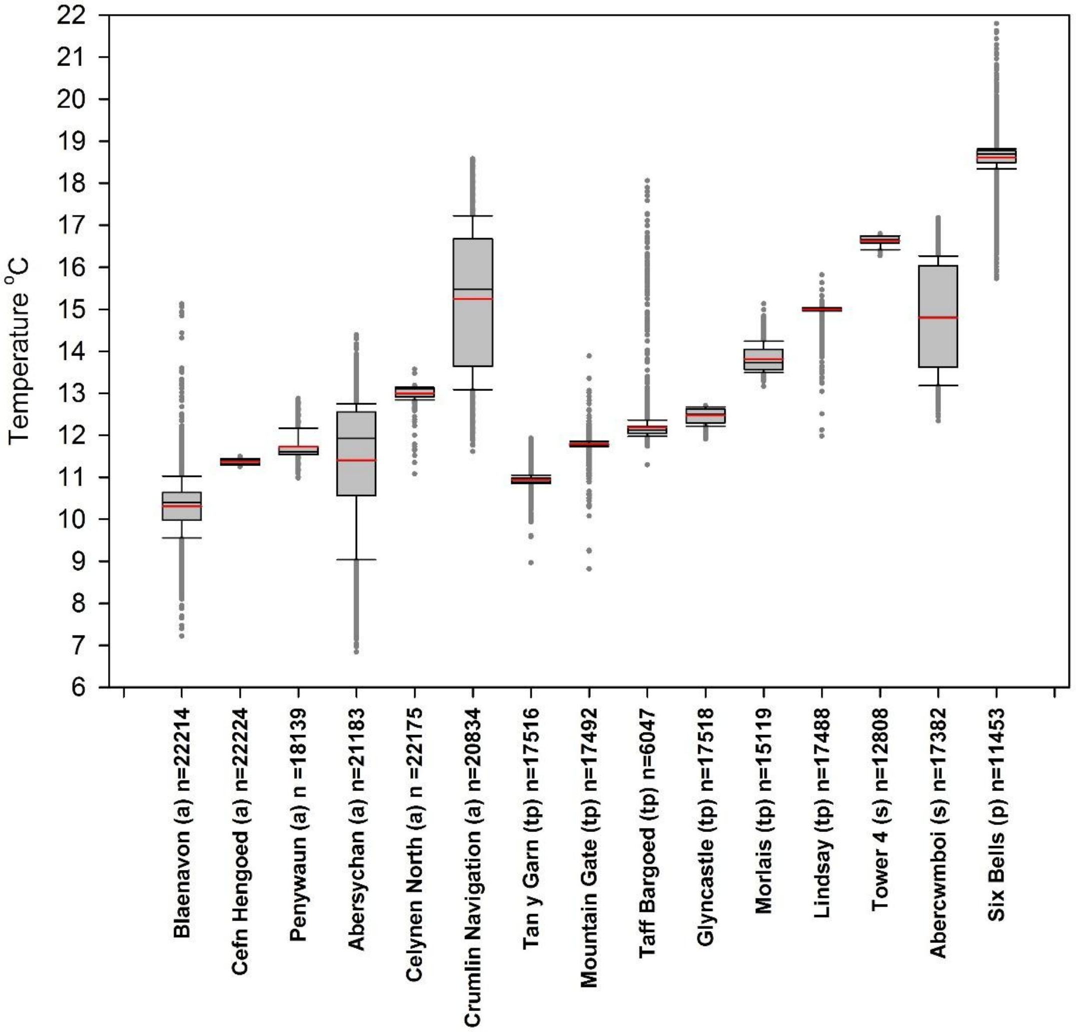

Figure 3. Box and whisker plot, based on in situ temperature loggers, showing variations within mine water temperatures in the South Wales Coalfield from data collected between July 2013 and October 2014. The mean of each dataset is indicated by the red line.

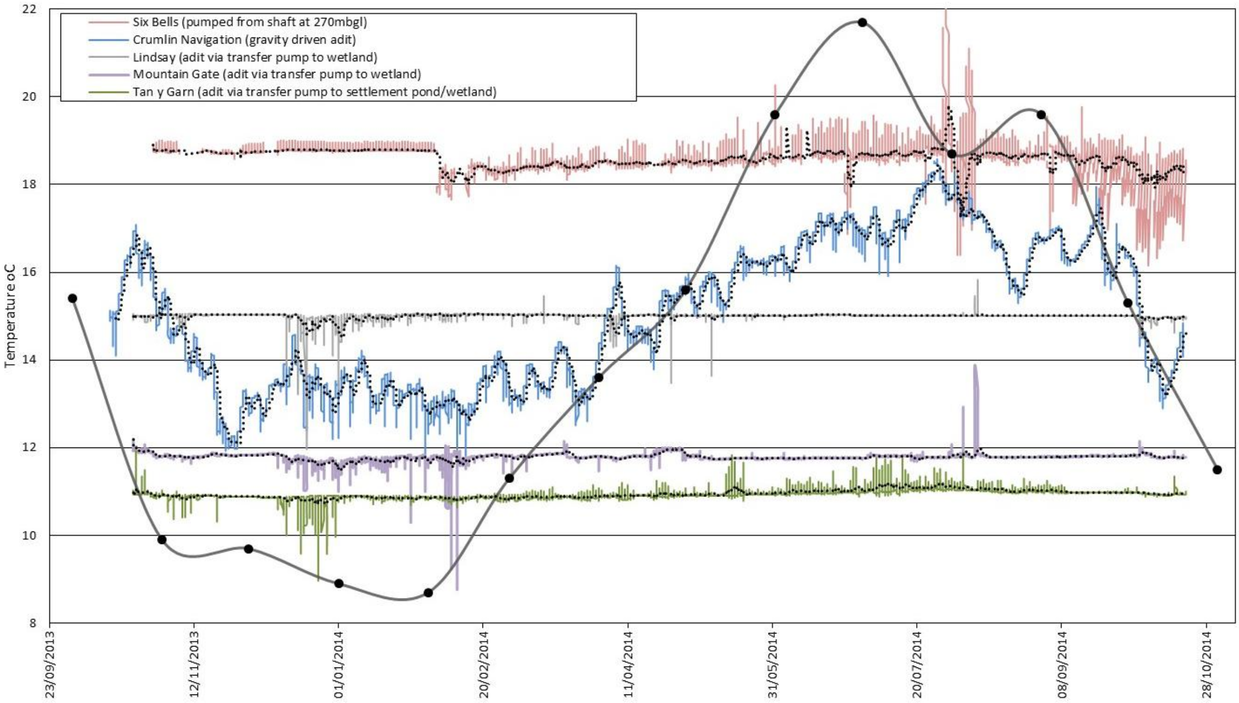

Figure 4. Time series mine water temperature data from a subset of monitoring sites (October 2013 to October 2014) compared to monthly mean atmospheric air temperature (Met Office). Each mine water time series is annotated with a 100 point moving average, black dotted line, to make trends move visible.

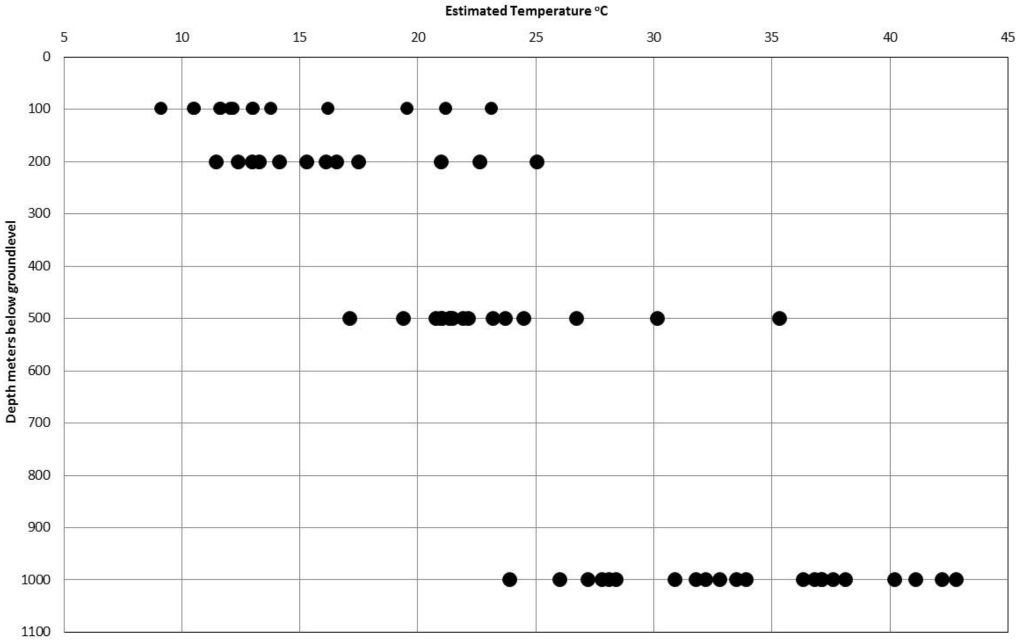

Figure 5. Groundwater temperature estimates from 100, 200, 500 and 1000 mbgl within the South Wales coalfield based on data from the British Geological Surveys 'Geothermal Catalogue' and 'RECALL' database and Busby et al., 2011.

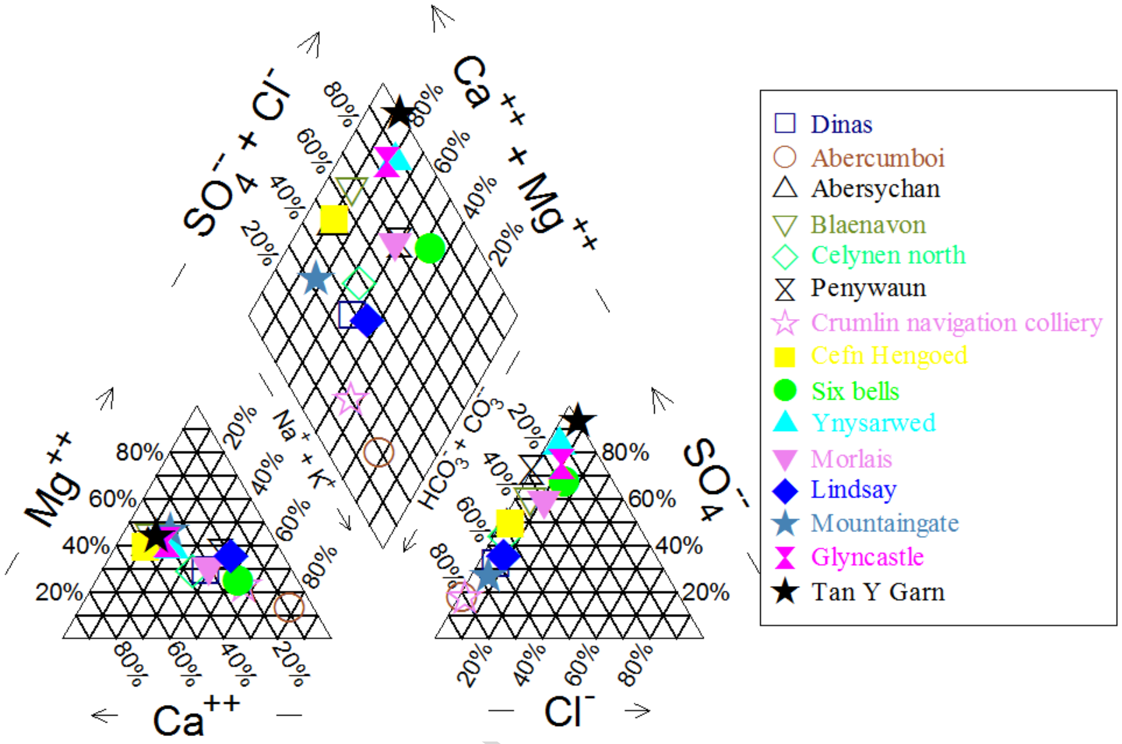

Figure 6. Piper diagram of mine water types in the South Wales coalfield (scale: 1 Unit = 10%)

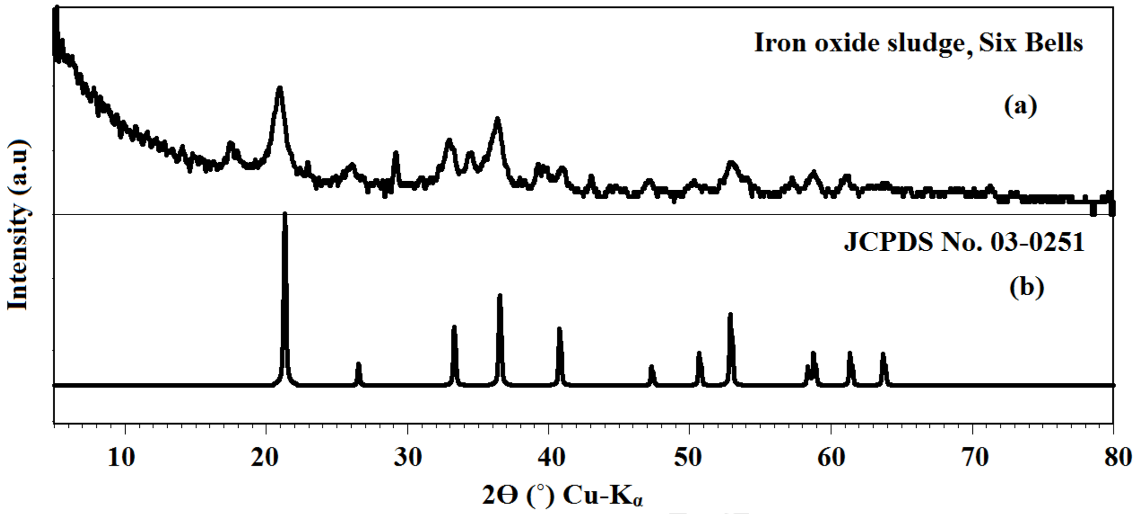

Figure 7. X-ray diffraction pattern of iron oxide sample collected from (a) Six Bells settlement pond and (b) reference pattern for goethite from JCPDS (Joint Committee on Powder Diffraction Standards) data base.

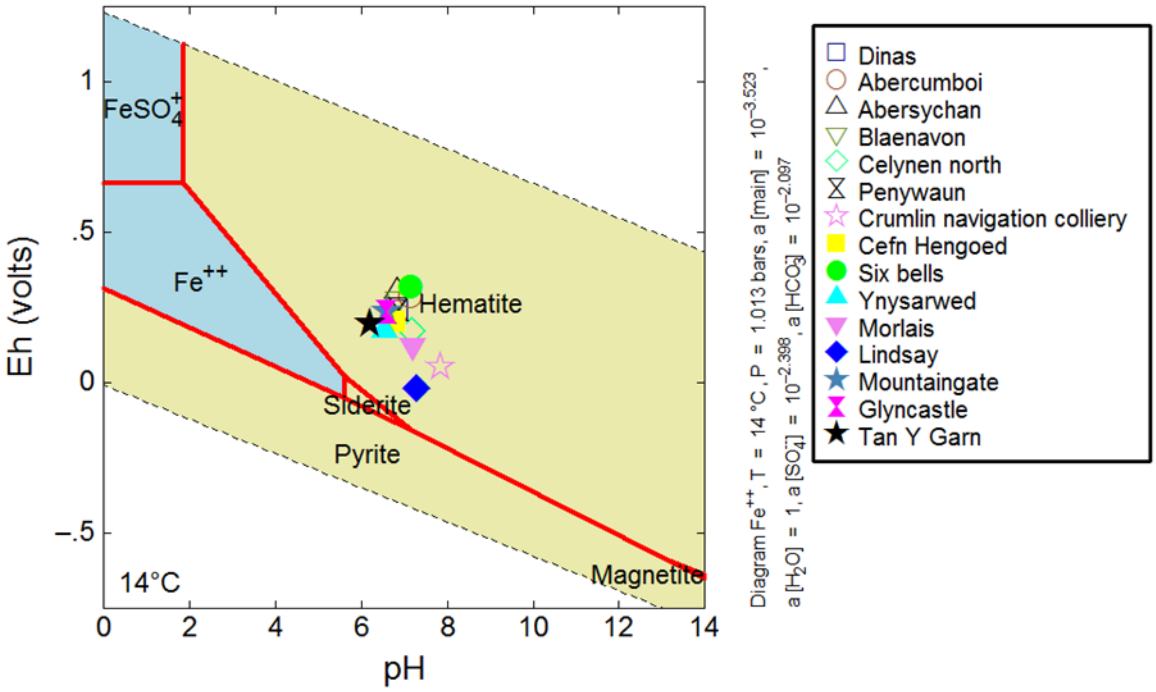

Figure 8. Eh-pH diagram of iron present in the mine waters

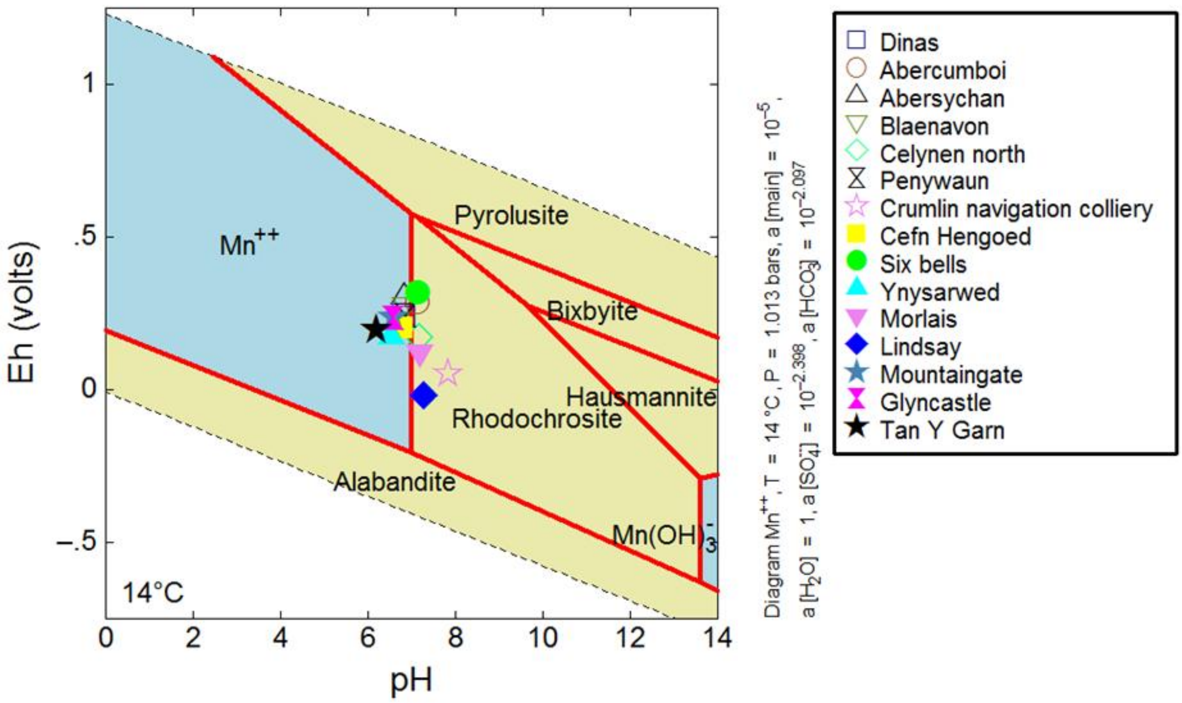

Figure 9. Eh-pH diagram of manganese present in the mine waters

Location	**Depth (m)**	**Installation Year**	**Mine Type**	**System Capacity (kW)**	**Use**	**Reference/Source**
Henderson Colorado, USA	Unknown	Early 1980	Metal	Unknown	Air heating	Jenson 1983
Heinrich Mine, Essen–Heisingen Germany	Uunknown	1984	Coal	350	Heating	Hall et al 2011
Springhill, Nova Scotia Canada	140	1986	Coal	111 heating/159 kW cooling	Heating/ cooling	Jessop et al 1995
Park Hills, Missouri, USA	133	1995	Coal	112	Heating	Hall et al 2011
Folldal, Norway	600	1998	Metal	18	Heating	Banks et al 2004
Shettleston Scotland, UK	100	1999	Coal	65	Heating	Banks et al 2009
Quebec, Canada	Flooded open pit	2006	Coal	36 apartments	Heating	Jessop et al 1995
Czeladź, Poland	200 m	2012	Coal	117 kW	Heating	REMINING-Lowex, 2012
Heerlen, Netherlands	700	2007	Coal	700	Heating/ cooling	Verhoeven et al 2014
Mieres, Spain	70	2009	coal	117	Heating/ cooling	Younger 2014
Dawdon,, England, UK	66.7	2011	Coal	12	Heating	Bailey et al 2013
Markham, England, UK	235	2012	Coal	20	Heating	Athresh et al 2015
Crynant, Wales, UK	65	2014	Coal	35	Heating	Seren Project data unpublished

Table 1. Summary of existing mine water open loop heating schemes

Sample ID		Dinas	Abercumboi	Abersychan	Blaenavon	Celynen north	Penywaun	Crumlin navigation colliery	Cefn Hengoed	Six bells	Ynysarwed	Morlais	Lindsay	Mountaingate	Glyncastle	Tan Y Garn	Tower No.4
Flow l/s (mean 1998-2014 Coal Authority)	L/s	25	n/a	230	40	50	n/a	n/a	100	50	25	125	20	10	15	2	n/a
Temperature (mean 2013-2014)	C	12.47	14.8	11.41	10.3	13	11.7	15.2	11.4	18.6	n/a	13.8	15.0	11.7	12.5	10.9	16.6
Temperature Number of readings	n	1	17382	21183	22214	22175	18139	20834	22224	11453	n/a	15119	17488	17492	17518	17516	12808
pH		6.83	7.15	6.83	6.87	7.16	6.87	7.83	6.79	7.13	6.53	7.18	7.27	6.59	6.58	6.18	6.95
Eh	V	0.237	0.284	0.301	0.279	0.17	0.24	0.052	0.2	0.315	0.175	0.12	-0.02	0.232	0.235	0.193	-16
TDS	mg/Ll	405	1089	489	366	715	1018	1195	468	1408	870	693	708	482	706	264	334
Dissolved oxygen	mg/Ll	0.42	6.1	7.633	8.9	1.03	5.25	0.02	1.01	6.76	3.21	0.69	0.1	2.76	0.65	0.58	2.6
HCO3-	mg/Ll	238	1202	316	161	427	394	1555	293	293	207	275	458	454	165	Nd	Nd
Na+	mg/Ll	45.95	340.3	13.92	9.518	111.2	176.9	286.2	18.7	384.2	73.65	112.8	114	27.33	51.05	9.922	68
Ca++	mg/Ll	38.24	35.77	90.97	61.28	111.9	94.29	104	92.88	154.6	135.9	86.99	54.83	77.1	113.3	40.15	48
Mg++	mg/Ll	20.76	32.06	45.24	37.3	52.54	91.35	64.1	44.18	104.9	78.73	53.88	59.29	58.65	69.93	24.62	19
K+	mg/Ll	10.9	36.06	22.75	13.86	14.13	30.3	42.22	10.6	71.8	18.82	28.67	54.97	24.54	15.32	7.112	18.4
Fe (Total)	mg/Ll	4.89	1.1	2.51	6.39	3.986	3.663.66	0.23	3.306	15.4	76.85 81.06	22.58	16.47	2.8	19.15	56.03	9.8
Fe (Dissolved)	Mg/L	4.31	0.02	2.1	5.63	3.7	2.2	0.04	3.0	5.74	76.85	19.62	14.8	2.6	16	Nd	Nd
Mn++	mg/Ll	0.7	0.22	0.46	2.14	0.93	1.9	0.23	0.53	0.48	1.56	0.82	0.58	1.21	1.57	2.35	0.9
As (Total)	mg/Ll	0.12	nd	0.1	0.11	0.11	0.089	0.096	0.1	0.1	0.155	0.11	0.125	0.12	0.126	0.142	0.12
Li+	mg/Ll	0.04	ND	0.08	0.06	0.09	0.07	0.32	0.03	0.25	0.08	0.06	0.04	0.02	0.07	0.003	0.031
Sr++	mg/Ll	0.32	0.4	0.94	0.32	0.78	0.55	1.5	0.69	1.69	1.09	0.63	0.35	0.61	1.26	0.15	0.22

F-	mg/L l	1.65	0.55	0.10	1.86	ND	3.55	2.65	1.30	24.3	2.56	0.1	0.3	0.07	0.13	0.13	0.36
Cl-	mg/L l	15.03	11.55	12.23	15.05	19.8	0	32.35	14.05	139.6	51	60.2	37.9	27	61.1	14.4	11.5
SO4--	mg/L l	97.47	208	243	223.1	283	802	258.4	240.5	861	1119	427.3	221.7	141	620.5	263	56.2
Water type		Na-HCO3	Na-HCO3	Ca-SO4	Mg-SO4	Na-HCO3	Na-SO4	Na-HCO3	Ca-SO4	Na-SO4	Mg-SO4	Na-SO4	Na-HCO3	Mg-HCO3	Mg-SO4	Mg-SO4	Na-SO4
calcium/sulphate ratio($\frac{Ca^{2+}}{Ca^{2+}+SO_4^{2-}}$)		0.28	0.15	0.27	0.22	0.28	0.11	0.29	0.28	0.15	0.11	0.17	0.2	0.35	0.15	0.13	0.46
sodium/chloride ratio ($\frac{Na^{+}}{Na^{+}+Cl^{-}}$)		0.75	0.97	0.53	0.39	0.85	1	0.90	0.57	0.73	0.59	0.65	0.75	0.5	0.46	0.41	0.85
Calcium /Magnesium ratio ($\frac{Mg^{2+}}{Ca^{2+}+Mg^{2+}}$)	0.35	0.47	0.33	0.37	0.32	0.49	0.38	0.32	0.4	0.37	0.38	0.52	0.43	0.38	0.38	0.28	0.35

Table 2. Water chemistry and temperature of mine water in South Wales Ccoalfield. (The values of water quality parameters presented are mean values of 3 sampling analysis, Nd-Not determined)

Mineral name	Saturation Index $(SI) = \frac{IAP}{K}$; Where, *SI*- Saturation Index, *IAP*-Ion activity product, *K*-Equilibrium Constant															
	Dinas	Abercumboi	Abersychan	Blaenavon	Celynen north	Penywaun	Crumlin navigation colliery	Cefn Hengoed	Six bells	Ynysarwed	Morlais	Lindsay	Mountaingate	Glyncastle	Tan Y Garn	Tower No.4
Aragonite	-1.05	-0.09	-0.63	-1.04	-0.05	-0.63	1.13	-0.72	-0.18	-1.23	-0.34	-0.16	-0.85	-1.25	ND	ND
Calcite	-0.88	0.07	-0.47	-0.87	0.12	-0.46	1.29	-0.55	-0.01	-1.06	-0.18	0.0005	-0.69	-1.08	ND	ND
Dolomite	-0.96	1.22	-0.17	-0.9	0.99	0.15	3.49	-0.36	0.93	-1.27	0.52	1.12	-0.43	-1.3	ND	ND
Pyrite	-92.78	-109.4	-108.3	-103.1	-81.08	-92.95	-64.52	-82.5	-114.5	-69.81	-67.94	-35.81	-87.81	-86.43	-69.61	-32.89
Goethite	6.2	6.8	6.8	7	5.8	6.1	4.5	5.2	8	5.2	5.8	3.6	5.1	5.9	4.5	2.641

ND-Not Determined

Table 3. Saturation Index values of the major minerals present in the mine water

Monitoring Location	**National Grid Reference (NGR)**	**Coal Authority, annual discharge data l/s 1998-2014**	**Annual mean monitored temperature °C**	**Thermal Capacity MWth**	**Number of building that can be heated based on annual UK household consumption of 18.6MWh**	**No of buildings within 500m buffer from monitoring point based on Ordnance survey data**
Abersychan (A)	SO2620103483	230	11.41	4.81	**437**	**334**
Cefn Hengoed (A)	ST1540096200	100	11.49	2.09	**190**	**278**
Celyenyn (A)	ST21228 97454	50	13.0	1.05	**95**	**375**
Morlais (A)	SN5718702207	125	13.82	2.61	**238**	**4**
Bleanavon (A)	SO2452608932	40	10.32	0.84	**76**	**134**
Abercwnboi (S)	ST0303399628	10	14.8	0.21	**19**	**139**
Crumlin Navigation (A)	ST2113498794	10	15.25	0.21	**19**	**191**
Pen y Waun (A)	SN9707805116	10	11.72	0.21	**19**	**56**
Lindsay (TP)	SN5911010772	20	15.0	0.42	**38**	**27**
Mountain Gate (TP)	SN6033111409	10	11.79	0.21	**19**	**27**
Tan y Garn (TP)	SN6302309788	2	10.94	0.04	**4**	**14**
Glyncastle (TP)	SN8314702823	15	12.47	0.31	**29**	**64**
Tower (S)	SN9261704282	Shaft – no pumping	16.63	n/a	**n/a**	**4**
Six Bells (P)	SO2201003410	50	18.61	1.05	**95**	**260**
Ynysarwyd (A)	SN8043201970	25	13.0	0.52	**48**	**1**
Taff Bargoed (TP)	ST1029099180	20	12.19	0.42	**38**	**10**
Sum Total of monitored discharges		**717 l/s**		**14.99**	**1362**	**1918**
Annual average flow data after closure based on 62 Wales Mine sites monitored by the Coal authority (1998-2014)		2025	13	**42.30**	**3848**	
Annual average flow data based on 320 pumped Wales Mine sites, while in operation, monitored by the Coal Authority (1948-1965)		3444	13	**71.98**	**6544**	

Table 4. Estimate of thermal heat potential from individual mine water discharges, and from cumulative outflow from the South Wales coalfield

Highlights

- Flooded coal mines offer significant potential for heat recovery in South Wales
- Between 42 and 72MW of heating energy could be generated
- Up to 6500 typical 3 bedroom homes could be supplied
- Contribution to heat from exothermic reactions considered minimal