Heat recovery potential of mine water treatment systems in Great Britain

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ABSTRACT

Treatment of pollution from abandoned coal mines often requires significant inputs of electrical power, particularly at sites where long-term pumping of mine water is required. Given the large fossil fuel generation element of the UK electricity supply network, this has a direct impact on carbon emissions. The potential for recovery of low enthalpy heat at mine water treatment sites in Great Britain, such that they could become net sources of energy during operation, rather than consumers, was explored using data from April 2014 to March 2015. To do this, an inventory of coal mine water treatment systems across England, Scotland and Wales was first collated, including key variables for each site. The heat energy which could potentially be recovered was then assessed against the energy consumption of each site and reviewed at a national scale. It was found that 47.5 MW of thermal energy was available for recovery from mine waters, compared to 2.3 MW of electrical power already committed for pumping and treatment of these waters. Recovery of thermal energy might be achievable by the use of heat pumps for space heating of nearby properties. Yet, because of the high carbon cost of UK grid electricity required to power heat pumps, this approach would offer only very modest CO_2 savings over domestic gas central heating. Calculations made in this paper suggests that just 0.33 kt CO_2 savings are achievable using this approach, compared to existing emissions of 10.8 kt CO_2 entailed by the pumping and treatment sites themselves.

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1. Introduction

Widespread closure of coal mines in Great Britain occurred in the latter part of the 20th Century. The subsequent flooding of mine workings, and recovery of mine water levels, gave rise to polluting surface discharges in the vicinity of many abandoned mines (Younger, 1997; Henton, 1981). Elsewhere, monitoring identified that rising water levels were at risk of causing outbreaks at the surface or pollution of groundwater in overlying aquifers (e.g. Neymeyer et al., 2007; Younger, 1993). The Coal Authority, an organization statutorily responsible for managing the legacy of abandoned coal mines in Great Britain, currently operates 64 pumping stations or treatment systems to tackle this issue. Research efforts have largely focused on improving treatment technologies and lowering operating costs in order that this legacy can be effectively managed with a lesser financial burden on the taxpayer. Recently, research has also been undertaken into resource recovery from such treatment systems, including the use of mine-water coupled heat pumps for space heating applications (Bailey et al., 2013). If commercially viable, heat recovery from mine water using heat pumps might offer a low-carbon alternative for space heating of homes and businesses in close proximity to treatment sites. This could offer a means of offsetting both financial and carbon emission costs of existing treatment systems.

Ground source heating and cooling is a well-established practice (e.g. Yang et al., 2010; Lund et al., 2004; Sanner et al., 2003) where heat energy can either be extracted or deposited within soils, rocks and/or groundwater, typically for space heating purposes. Extraction of heat from depth benefits from geothermal gradients, which in coal measures strata of England has been determined as typically 3.7 °C/km, although this varies depending on the individual location (Banks, 2008; Prestwich, 1884). Although feasible to extract heat from ground sources for direct applications, the relatively low temperature of the shallow subsurface in Great Britain necessitates the use of heat pumps to provide sufficient temperatures for conventional space heating systems (typically <55 °C) (Banks, 2008). For details of heat pump mechanics and ground source configurations the reader is directed to Banks et al. (2003).

Deep coal mines in Britain, and more widely throughout Europe and North America, have extensively altered the hydrogeological properties of coal measures strata (Neymeyer et al., 2007). As a result, these previously low-permeability strata are now host to vast networks of roadways, open voids and goaf (collapsed roof strata), all of which have enhanced hydraulic conductivity (Adams and Younger, 2001). These phenomena have been termed 'anthropogenic aquifers' by Adams and Younger (2001), given that the changes have solely arisen from human interventions. Sinking of boreholes into these anthropogenic aquifers can provide access to vast quantities of thermal energy

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(Watzlaf and Ackman, 2006). In particular, the high regional transmissivity of flooded workings allows circulation of heat by both convection and conduction, and the large water–rock interface for heat conduction rapidly replenishes the resource (Banks et al., 2003). It has been estimated that 3000 MW$_t$ heat energy is available in the waters of flooded coalfields of Europe (Díez and Díaz-Aguado, 2014).

Flooded workings not only offer a source of low-grade heat, but can also be used for disposal of heat, from air conditioning units for example (Preene and Younger, 2014; Watzlaf and Ackman, 2006). In fact, it has been demonstrated at Springhill, Nova Scotia, that dumping of heat into coal mine waters during the summer can act to balance heat extraction from the same waters during winter (Jessop et al., 1995).

Despite the potential for waters within, and flowing from, abandoned mines to act as ground source heat sources, as of 2013 there were less than 20 examples of mine water sourced systems internationally (Preene and Younger, 2014). Similar to conventional groundwater-based open-loop ground source heat systems, exploitation of mine water often utilizes well-doublet systems, which intersect mine workings for extraction and re-injection of water (Verhoeven et al., 2014; Banks et al., 2009; Jessop, 1995). Drilling of abstraction and recharge wells can significantly add to capital costs, which may explain the paucity of examples in the literature (Preene and Younger, 2014). Additionally, perpetual pumping consumes significant quantities of electricity, reducing overall system efficiency. Nonetheless, there are many sites in coalfield areas where water either discharges by gravity, or is pumped to the surface for operational or environmental reasons. Under these circumstances, any installed heating scheme would neither entail capital costs of well installations, nor suffer long-term energy inefficiencies associated with abstraction (Hall et al., 2011).

The aim of the investigation presented here was to make an assessment of the potential thermal energy available in British mine waters, and to explore to what extent this might be harnessed to offset the electrical power currently used for the purposes of pumping and treating these mine waters. The investigation was conducted at a national scale to provide an overview of (a) current power consumption (and associated equivalent carbon emissions), (b) potential thermal energy available, and (c) the potential reduction in equivalent carbon emissions via utilization of the thermal energy in space heating installations. Recognizing that power consumption and thermal energy available may vary widely between sites, the available data are divided into 4 broad categories:

1. Pumped discharges that receive active treatment
2. Pumped discharges that receive passive treatment
3. Pumped discharges that receive no treatment
4. Gravity discharges that receive passive treatment

In addition, figures and tables show data on an individual site basis. It is worth noting also, that there are several hundred untreated gravity discharges, but as these are not generally monitored they were not assessed in this study.

2. Materials and methods

2.1. Mine water data

12 months of data, covering the period 1st April 2014 to 31st March 2015, are presented for raw mine water chemistry and flows. Analysis of total metal and anion concentrations were conducted by an accredited laboratory in the UK. Samples for metals analysis were acidified and transported in sealed cool boxes. Total alkalinity measurements were made at the time of sample collection using a Hach™ digital titrator with 1.6 N sulfuric acid and bromcresol green-methyl red indicator, to a pH 4.5 end-point. Additional field variables, including temperature, conductivity and pH, were measured either by calibrated probes (typically Schlumberger Water Services Divers™ for temperature) installed within treatment systems, or using a Myron 6P Ultrameter handheld

device where probes were not present. Flow measurements were made using one of two methods depending on site conditions: (1) flow meters within pipes (e.g. electromagnetic) or (2) sharp-crested V-notch weirs. Data are presented for flows averaged over a year (i.e. including times when pumps were not running), because it is noted that most pumped sites receive only intermittent pumping, for example to benefit from lower cost electricity tariffs.

Potential power from individual mine water sources was estimated using the following expression (after: Banks et al., 2003):

$$P = Qc\Delta T$$

where Q = flow in liters per second; c = specific heat capacity in kJ/(kgK) (assumed as 4.2, although may be <5% lower for hypersaline waters (Jamieson et al., 1969)); ΔT = temperature change of source in °C, and P = power in kW$_t$ ($_{t\,=\,thermal}$).

Temperature data were collected continuously at some sites as a secondary function of monitoring equipment. More sporadic measurements were made at others (typically where number of measurements (n) <10; see Tables S1–S4 in supplementary information). In such cases, and in order to use the most reliable data available, temperature data were taken from measurements made between 2010 and 2015. Given the timescales since widespread coalfield abandonment in Britain, the majority of mine water pumped flows and discharges are well established (Wood et al., 1999). Consequently, it is likely that these measurements are representative of the long-term mine water flows.

2.2. Power consumption data

All electricity consumed by mine water pumping stations and treatment systems were gathered via metered connections to the UK National Grid electricity supply network (which covers Great Britain and Northern Ireland). Meter readings were taken on a monthly basis, between 1 April 2014 and 31 March 2015. Power consumption data for the entire year have been used for calculations, with mean values determined to give represented kW ratings, although it is acknowledged that at many sites power consumption is not continuous.

3. Results and discussion

3.1. Physical and geochemical characteristics of mine waters in Britain

Deployment of treatment systems to tackle coal mine waters in Great Britain has targeted the use of passive technologies where possible. Passive treatment entails harnessing natural processes without the need for chemicals or energy (PIRAMID Consortium, 2003). This is primarily in order to keep operational costs as low as possible. Typical treatment system objectives are to remove iron, and elevate pH where required, in order to comply with environmental regulations. For the systems considered here passive treatment comprises aeration (bay cascades), settlement lagoons and aerobic wetlands in the majority of cases. Exceptions to this are where discharges have significant mineral acidity, including Tan-y-Garn and sites at Pelenna (see Fig. 1), where anaerobic, compost based Reducing and Alkalinity Producing Systems (RAPS) are deployed to remove metals as sulfides while simultaneously generating bicarbonate alkalinity (see: Tuttle et al., 1969). It is apparent from Table 1 that in reality it is necessary to pump mine water to a suitable location for passive treatment in many cases (approximately two thirds of all treatment schemes), and so these systems are not entirely passive in the strictest sense.

Where mine water is heavily polluted and flow-rate is high, passive treatment has not always been feasible and therefore at these sites active treatment technologies have been installed. All active treatment systems discussed here consist of aeration and settlement ponds, together with dosing with oxidizing agents (usually hydrogen peroxide) or alkali (hydrated lime or sodium hydroxide) in order to increase

rates of ferrous iron oxidation and/or raise pH. Exceptions are Dawdon and Ynysarwed (Fig. 1), which are treated using High Density Sludge (HDS) plants.

At 2 of the 64 sites considered here (Kimblesworth and Chester South Moor; see Fig. 1 for locations) mine water is pumped to surface and discharged directly to a watercourse, without treatment.

Table 1 shows summary flow, temperature and geochemical data for all mine waters that were included in this analysis. The vast majority of mine water flows treated have circum-neutral pH (overall mean: 7.0; range: 5.75–7.75) and elevated alkalinity. While oxidation of pyrite within coal measures strata is well known to generate acidity (e.g. Banks et al., 1997), dissolution of carbonate minerals, usually in strata overlying the coal mine workings, serves to buffer acidity (Younger, 1995).

The two pumped mine waters that do not receive treatment have amongst the highest flows (160.0; 229.1 L/s), although low iron concentrations (4.0; 4.3 mg/L) (Table 1). As a consequence of the low iron concentrations, they are discharged to watercourses without treatment. Pumped mine waters receiving active treatment have the next highest flows (mean = 46.6 L/s; median = 41.3 L/s). It is these waters that also have the highest iron concentrations (mean = 45.2 mg/L; median = 41.3 mg/L), and it precisely this combination of high flow and high pollutant concentration that means they require active treatment. Pumped mine waters receiving passive treatment have lower flow rates and lower iron concentrations than pumped and active treated mine waters (Table 1), but their temperatures are similar to those waters receiving active treatment (mean temperature = 13.2 °C for passive and 12.7 °C for active; Table 1). Gravity mine water flows have temperatures that are, on average, 1–2 °C lower than pumped mine waters (mean temperature = 11.5 °C; Table 1). This is probably due to gravity flows being in cooler near-surface environments for a longer period of time prior to discharge, compared to pumped waters from depth.

Additionally, there will be small temperature increases arising from the act of pumping deep mine waters.

One final, important, observation is that there is a pronounced difference in electrical conductivity (EC) between pumped flows at active and passive treatment sites (6179 and 3804 μS/cm, respectively) and gravity flows (981 μS/cm). Mine waters from greater depth tend to have higher conductivities due to longer rock-water interaction, greater potential influence of saline waters, and inflows of strata water with higher conductivity. This is clearly shown when electrical conductivity is logged down a mine shaft water column, an example of which is shown in Fig. S1 (see supplementary information). Because these deeper mine waters tend to have higher temperatures as well there is a strong positive correlation between these two variables, as illustrated in Fig. 2 (and also on Fig. S1). The significance of this in the context of harnessing thermal energy from these waters is that these geochemical characteristics may pose a risk of operational problems with heat pumps, such as corrosion, encrustation or blocking of heat exchangers (Preene and Younger, 2014). This is due primarily to the higher salinity and iron concentrations of these deeper waters.

In relation to operational problems due to poor water quality (reflected in high electrical conductivity), Bailey et al. (2013) and Banks et al. (2009) both reported on trials of heat exchangers used to recover energy from high electrical conductivity water. In both cases, as long as the raw mine water was kept under anoxic conditions, thus preventing precipitation of hydrous ferric oxides (HFO), heat exchangers operated without problems, for around 10 years in the cases reported by Banks et al. (2009). When heat exchangers were used on the same waters after they had been exposed to atmospheric conditions, operational problems ensued due to HFO precipitation following ferrous iron oxidation (Bailey et al., 2013; Banks et al., 2009). For the purposes of this research, it is assumed that any heat recovery system would therefore be located in-line between the mine water source,
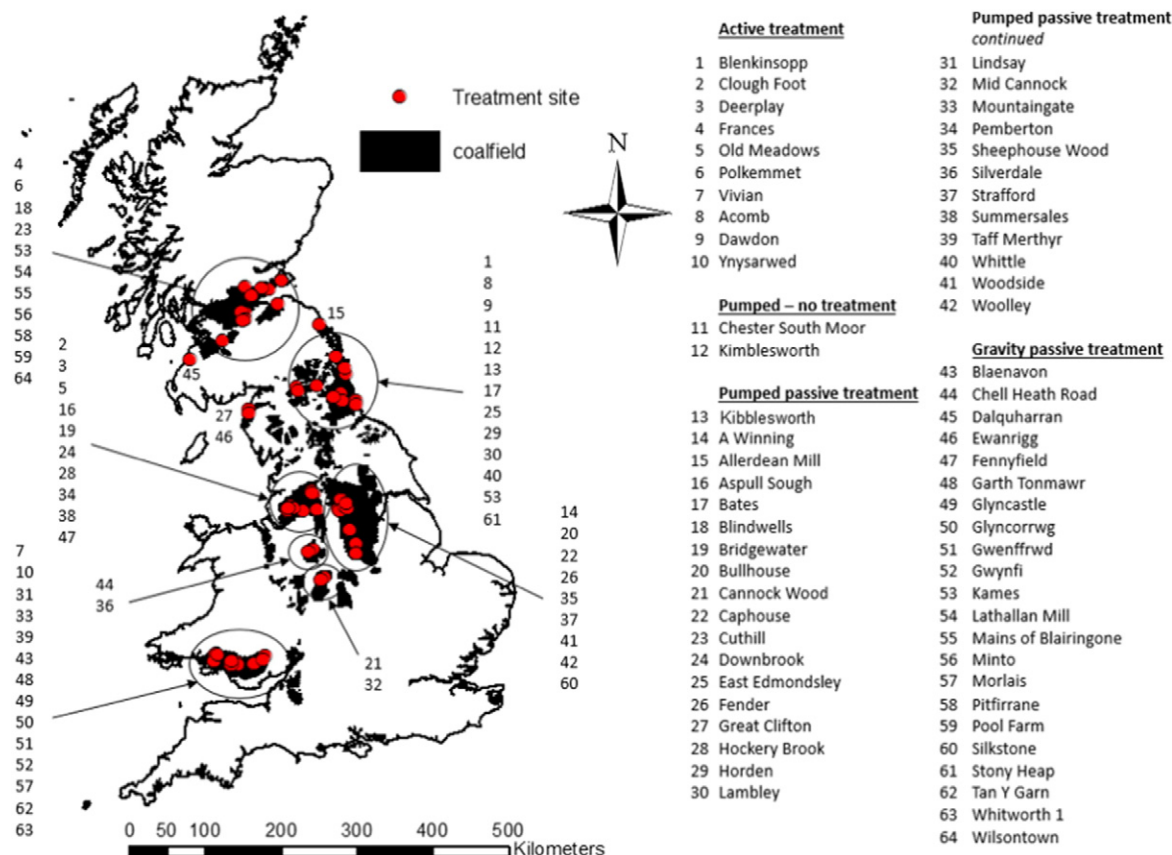

Active treatment

1 Blenkinsopp
2 Clough Foot
3 Deerplay
4 Frances
5 Old Meadows
6 Polkemmet
7 Vivian
8 Acomb
9 Dawdon
10 Ynysarwed

Pumped – no treatment

11 Chester South Moor
12 Kimblesworth

Pumped passive treatment

13 Kibblesworth
14 A Winning
15 Allerdean Mill
16 Aspull Sough
17 Bates
18 Blindwells
19 Bridgewater
20 Bullhouse
21 Cannock Wood
22 Caphouse
23 Cuthill
24 Downbrook
25 East Edmondsley
26 Fender
27 Great Clifton
28 Hockery Brook
29 Horden
30 Lambley

Pumped passive treatment
continued

31 Lindsay
32 Mid Cannock
33 Mountaingate
34 Pemberton
35 Sheephouse Wood
36 Silverdale
37 Strafford
38 Summersales
39 Taff Merthyr
40 Whittle
41 Woodside
42 Woolley

Gravity passive treatment

43 Blaenavon
44 Chell Heath Road
45 Dalquharran
46 Ewanrigg
47 Fennyfield
48 Garth Tonmawr
49 Glyncastle
50 Glyncorrwg
51 Gwenffrwd
52 Gwynfi
53 Kames
54 Lathallan Mill
55 Mains of Blairingone
56 Minto
57 Morlais
58 Pitfirrane
59 Pool Farm
60 Silkstone
61 Stony Heap
62 Tan Y Garn
63 Whitworth 1
64 Wilsontown

Fig. 1. Coal mine water pumping and treatment sites in Great Britain.

Table 1
Summary flow and physicochemical data for the 4 categories of mine waters (see Tables S1–S4 in supplementary information for complete data).

	Flow rate (L/s)	n	Temperature (°C)	n	Total iron (mg/L)	pH	EC (μS/cm)	Alkalinity (mg/L as CaCO₃)	n (Fe, pH, EC, Alk)
Pumped and active treatment (n = 10)									
Mean	46.6	88	12.7	2865	45.2	6.67	6179	281	36
Median	41.3	78	12.3	115	29.8	6.76	1844	242	32
Min	21.9	34	9.6	1	14.3	5.75	749	38	16
Max	108.9	190	18.7	12,857	106.4	7.41	44,344	754	68
Pumped and passive treatment (n = 31)									
Mean	45.7	78	13.2	2550	19.2	7.1	3857	486	19
Median	23.3	39	12.7	4	15.05	7.1	1923	437	15
Min	0.2	7	9.9	1	3.6	5.8	419	94	13
Max	294.6	330	16.9	35,600	65.4	7.6	33,366	1703	64
Pumped and no treatment (n = 2)									
Mean	194.6	1	13.1	1	4.15	7.29	2449	680	16
Median	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Min	160.0	1	12.7	1	4.0	7.27	1908	625	15
Max	229.1	1	13.5	1	4.3	7.31	2990	735	16
Gravity flow and passive treatment (n = 21)									
Mean	20.1	58	11.5	14,247	20.6	6.92	981	190	30
Median	14.5	25	10.9	8952	15.9	6.96	971	155	28
Min	2.4	4	9.8	1	4.1	6.42	407	33	12
Max	75.6	516	15.1	38,783	74.8	7.46	2191	595	84

Notes: n = number of measurements at individual sites; EC = electrical conductivity; Alk = alkalinity.

and treatment system. This would prevent exposure of mine water to atmospheric oxygen, which may cause precipitation of HFO precipitates which could cause fouling of the heat exchanger.

3.2. Mine waters as a thermal asset

Mean air temperatures in Great Britain mean that space heating could be used in homes and businesses throughout a significant proportion of the year. Mean temperatures between November and April 2014 (inclusive) were 7.05 °C in England, 6.65 °C in Wales and 5.03 °C in Scotland (Kendon et al., 2015). There is less of a requirement for space cooling, although this demand can be important in southern parts of Great Britain and, in particular, within the urban heat island of London (Clarkson et al., 2009; Fry, 2009).

Unlike surface water temperatures, mine waters show much less pronounced seasonal variations, due to thermal damping of geological strata (Banks et al., 2003). Fig. 3 provides a clear example of this, using mine water and adjacent air temperature data for the Blindwells site in East Lothian, Scotland. As a result, mine water temperatures are higher than mean surface temperatures during the winter (i.e. December–February in Fig. 3) when the heating requirement is greatest, leading to improved thermodynamic efficiency over air-sourced systems. Measured mine water temperatures vary between 9.7 and 18.7 °C, which is somewhat higher than the mean annual air temperature shown in Fig. 3.

These higher temperatures are likely a result of subsurface hydrogeology and interaction with geothermal gradients, in addition to the effects of pumping. Deeper waters are likely to be subject to a greater effect from geothermal gradients, but also suffer from increased mineralization, for example due to interactions with deep saline groundwater (Banks et al., 1997). As shown in Fig. 2, there is a good correlation between temperature and conductivity.

3.3. Electrical power consumption and thermal power potential at mine water treatment sites

Power consumption data display high variability between sites. There are 21 sites where no pumping takes place, and treatment is provided entirely by passive processes. Yet, at the other end of the scale, large pumping stations at Kibblesworth (Durham), Woodside (Nottinghamshire) and Woolley (Yorkshire) all consumed more than 2MWh of power between April 2014 and March 2015. All three pumping stations were installed to control water levels in deep abandoned coal mines. Active treatment processes also have substantial power requirements, with the Dawdon High Density Sludge (HDS) facility consuming in excess of 1 MWh over the same period, with an additional 0.8 MWh attributed to its pumping station.

For the purposes of this analysis, thermal energy available in mine waters is calculated based on a 4 °C drop in mine water temperature, which would provide a comfortable margin against icing and is
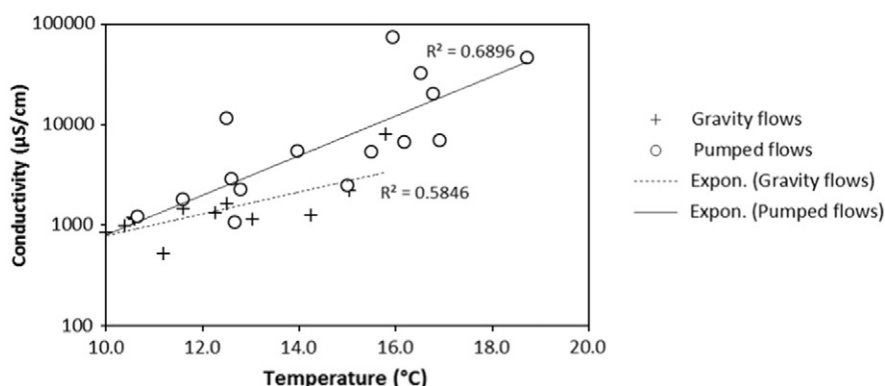

Fig. 2. Relationships between temperature and conductivity for mine waters at pumping stations and treatment systems.
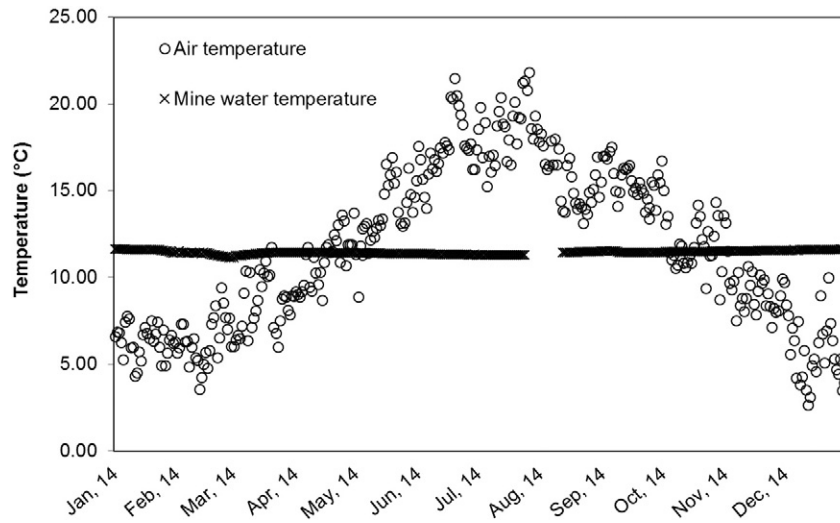
Fig. 3. Raw pumped mine water and air temperatures at Blindwells, East Lothian (daily averages during 2014).

comparable to Banks et al. (2009) who showed extraction of ~4 °C from a groundwater source.

Many larger power consumers also offer the greatest heat resource because the mine waters are often pumped from depth and flows are typically large. For example, the potential power recoverable by dropping temperatures by 4 °C is 4.85 MW_t at Kibblesworth and 806 kW_t at Woolley. Mean temperatures at these sites are 14.8 °C and 15.5 °C, respectively, both of which are in the upper third of temperatures measured.

This is not always the case, however, particularly for large gravity flows. Here, it may be feasible to harness an entirely renewable source of energy if heat pumps are coupled to a renewable supply of electrical power, such as a micro-hydroelectric scheme. For example, a gravity fed treatment system at Morlais in South Wales would yield 2.90MW_t by lowering the temperature of its raw flow by 4 °C. With mean temperatures of 14.1 °C, this passive site offers substantial quantities of thermal energy which might be recovered at a high efficiency by heat pump apparatus. Fig. 4 shows the comparison between the average power consumed by sites, compared to the thermal power which might be recoverable from them.

Additional benefits of harnessing gravity flows are that they are continuous sources of heat which could be accessed on-demand. Pumped flows, however, are typically intermittent, meaning that to satisfy demand when pumping was not undertaken, either a heat recovery system would require a large thermal store; or, changes to pumping regimes would need to be made.

The total low-grade thermal energy of all the mine waters considered in this investigation was 47.5 MW_t for the period 1 April 2014
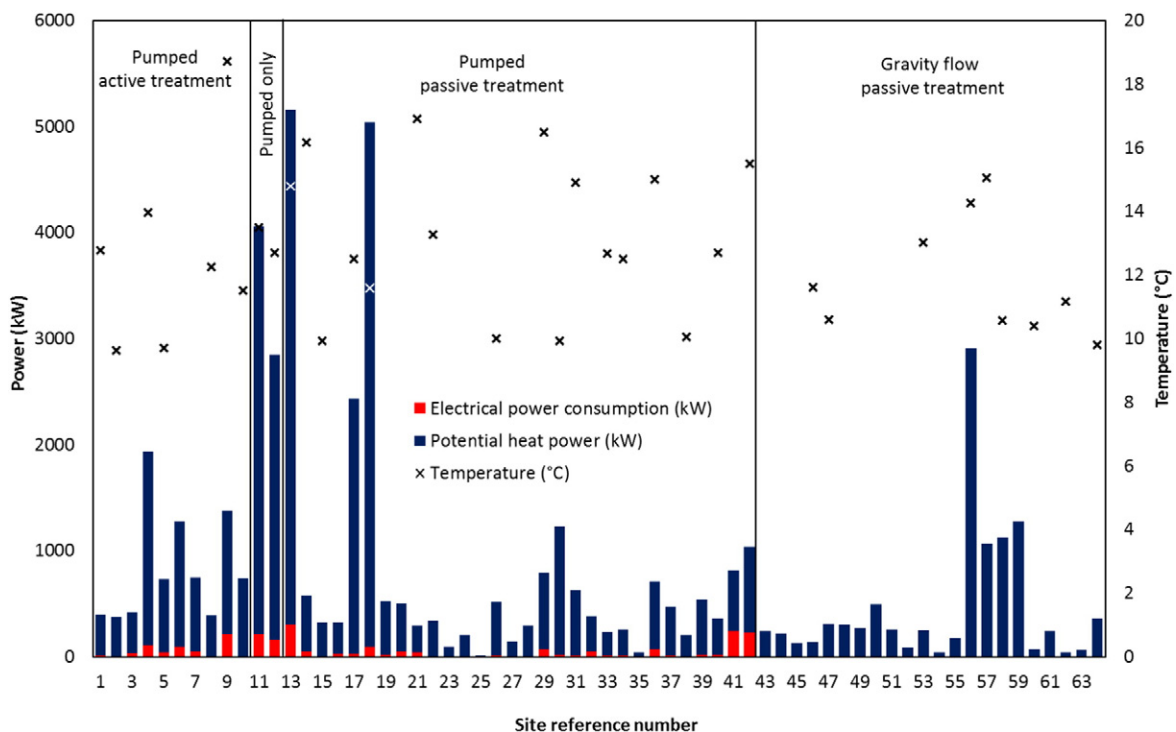

Fig. 4. Power consumption by pumping stations and treatment sites, compared to thermal power available from extracting 4 °C from mine water flows.

and 31 March 2015, as shown in Table 2. As a breakdown, this thermal power was split between sites where there was mine water pumping with active treatment was 7.8 MW$_t$, compared to sites with mine water pumping with passive treatment (23.0 MW$_t$) and gravity fed passive treatment 10.0 MW$_t$. The high-grade electrical energy used at these sites was 2.3 MW on average over the same period, as noted in Table 2.

3.4. Offsetting carbon emissions of mine water pumping and treatment

The analysis above suggests that the prospect of utilizing the thermal heat energy of mine waters appears attractive, especially as mine waters are a pervasive form of pollution, often flowing unabated for decades or centuries (Younger, 1997), and therefore they could be a long-term source of energy. Ultimately the attraction is that use of this alternative energy source could result in a reduction in carbon emissions from mine water pumping and treatment operations, and a reduction in emissions from current heating systems that this thermal energy might replace. To quantify the reduction in carbon emissions that might result from utilizing thermal energy of mine waters it is necessary to consider the CO_2 emission equivalent of (1) harnessing mine water thermal power (2) the power currently used at mine water treatment sites, and (3) the power used in existing heating facilities that mine water thermal heat might replace.

In 2014, grid-connected electricity generation in the UK (the administrative network area which includes Great Britain) comprised of coal fired (30%) and gas fired (30%) generation, in addition to nuclear (19%) and renewable sources (19.1%) with 'other fuels' occupying the remaining 2.6%, all as GWh (DECC, 2015a). DECC (2015b) provided a conversion factor which allows electrical power consumption in kWh to be converted to CO_2 emissions, based upon the current energy mix of grid-connected generation. The conversion factor calculated by (DECC, 2015b) is 0.5331 kg CO_2/kWh, and that figure was used in this analysis. Thermal heat in mine waters would most logically be used in space heating applications that would replace existing gas-fired heating systems in premises in close proximity to the mine waters. Gas-fired heating systems emit less CO_2 per kWh than electrical energy from the national grid, and therefore have a much lower CO_2 emission equivalent than grid-connected electricity; 0.1846 kg CO_2/kWh (DECC, 2015b).

Heat pumps for space heating do require some electrical energy to operate. In terms of net reduction in carbon emissions the difficulty is that this is electrical energy from the UK national grid, and therefore has the higher CO_2 emission equivalent (0.5331 kg CO_2/kWh) than the gas-fired heating systems (0.1846 kg CO_2/kWh) that mine water space heating could replace (DECC, 2015b). To calculate the net CO_2 emission equivalent of a space heating system driven by mine water it is necessary to understand how much electrical energy is required to power the system. The energy generated by a space heating system, as heat, is typically considered to be several times greater than the energy required, as electricity, to power the system. This ratio is known as the Coefficient of Performance (CoP), and the average reported from monitoring of domestic heat pumps in the UK, which typically use shallow ground sources, was 2.82 (range = 1.55–3.47) (EST, 2016). Mine waters

are typically sourced from greater depths than traditional shallow ground sources, thereby benefiting from geothermal gradients. On this basis, a slight improvement in efficiency may be expected in a mine water source heat pump and, for the purposes of this study, a CoP of 3 is assumed. According to the current carbon rating of grid electricity, this equates to 0.1777 kg CO_2/kWh of thermal energy provided by the heat pump.

Given the values for CO_2 emission equivalents above, and this understanding of the electrical energy required versus heat energy generated with a mine water space heating system, it is then possible to calculate the hypothetical net carbon reduction that would result from utilizing the heat energy of the mine waters shown in Table 1 for space heating, as an alternative to gas-fired heating systems.

The total CO_2 emission equivalent of the electrical energy used for pumping operations and active treatment of all the mine waters considered here was 10.8 kt CO_2/annum between April 2014 and March 2015 (Table 2). Unsurprisingly, the largest power consumers are the greatest contributors, leading to emissions of 7.5 kt of CO_2 per annum for the ten largest pumping stations. Active treatment at the Dawdon site results in 540 t of emissions alone, which does not consider secondary emissions related to production and transport of chemical reagents such as lime, for example. A further 438 t of CO_2 are attributable to the pumping station at this site.

The total net reduction in CO_2 emission equivalent by utilizing the thermal energy in mine waters for space heating, in place of gas-fired space heating, is 0.33 kt CO_2/annum, as shown in Table 2 and Fig. 5. Therefore, despite there being a substantial quantity of thermal energy available at mine water treatment sites (Table 2), utilizing this thermal energy for space heating (as an alternative to gas-fired heating) would result in a net reduction in carbon emission equivalents at mine water treatment sites of only 3%. In all likelihood achieving such a reduction may well not even be possible for practical reasons. For example, at many sites there may not be a demand for space heating at premises that are close enough to the mine water discharge to make space heating financially viable and, heating would only be required seasonally.

Whilst there would still be benefit to pursuing this as a means of making an incremental step towards carbon neutral mine water treatment, the limitations of use to space heating, and the comparatively low carbon equivalent emission of gas-fired heating systems, would mean that other measures would need to be implemented to make major strides towards carbon neutral mine water treatment. In particular, increasing heat pump performance so that higher CoP is achievable, or by reductions in carbon footprint of grid electricity would directly increase the carbon saving potential. Other options to reduce carbon emissions from mine water treatment operations might include identifying ways to reduce the power consumption at treatment sites. Obvious options to achieve this would be (a) reducing energy for pumping by allowing controlled rebound wherever it is possible without risking environmental damage and (b) moving, wherever feasible, to passive mine water treatment. Alternatively, it may be possible that off-grid renewable energy sources could be used as the source of energy required for the space heating system (REALL, 2007).

Table 2
Summary data for thermal energy available, and electrical energy consumed, at British mine water pumping and treatment sites and gravity discharges, and carbon equivalent reductions and emissions (see text for further details).

| Energy available at mine water sites and carbon equivalent reductions possible		Energy consumed at mine water treatment sites and carbon equivalent emissions	
Low-grade thermal energy available per 4 °C drop in mine water temperature:	47.5 MW$_t$	High-grade electrical energy used for mine water pumping and treatment:	2.3 MW
Possible energy uses:	Space heating to replace gas-fired heating	Possible energy uses:	Multiple
Net carbon reduction:	0.33 kt CO_2/annum	Net carbon emissions:	10.8 kt CO_2/annum
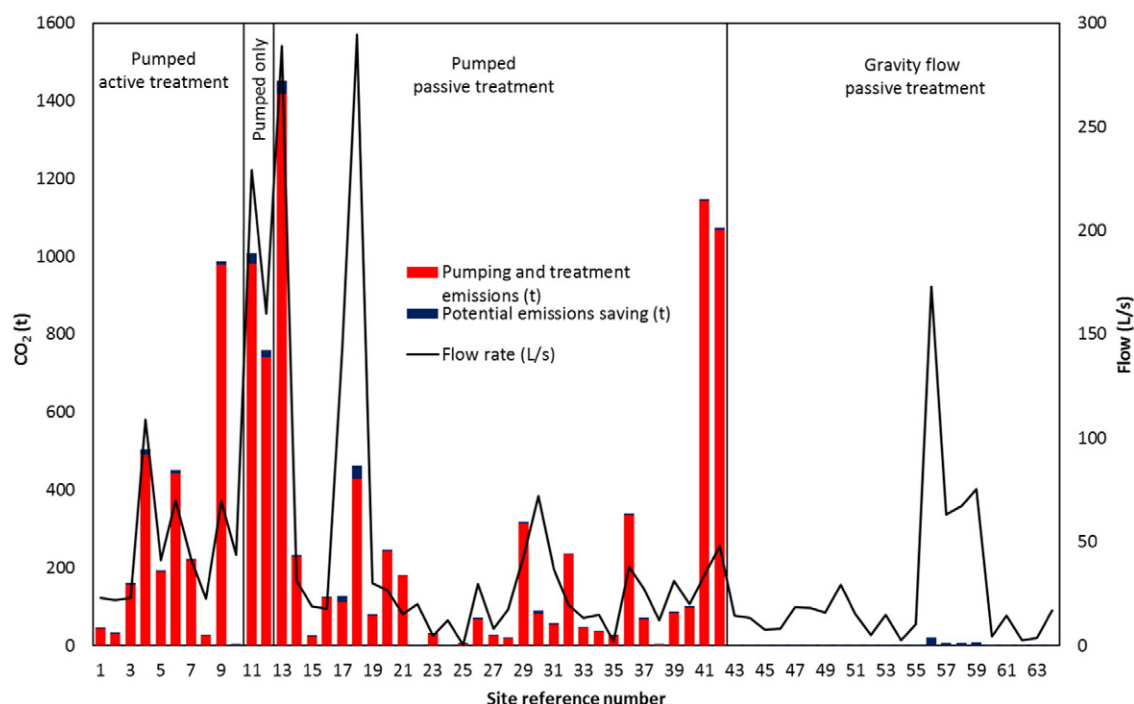
Fig. 5. Carbon emissions of pumping stations and treatment systems vs. potential carbon savings via use of heat recovery, assuming 1/3 of heat output is provided by UK electricity supply network.

4. Conclusions

61 mine water treatment systems and a further 3 pumping stations, where no water treatment is provided, are currently operational across the coalfields of Great Britain. These sites deal with flows from largely abandoned coal mines, and at many sites pumping and active treatment processes consume significant quantities of electrical power. This has a knock-on effect on carbon emissions, given that the UK electricity supply network is estimated to emit 0.5331 kg CO_2 for every kWh of electrical energy consumed. Yet, mine water flow and temperature data presented in this paper suggest that significant thermal energy exists, which, if recovered, might be used to offset this demand. As much as 47.5 MW_t energy was found to be available at mine water treatment sites across Great Britain by extracting 4 °C from flows. This is significantly in excess of the power consumed by pumping and treatment, albeit in low-grade heat rather than electrical form. Further analysis was undertaken to assess how the use of mine water coupled heat pumps in place of gas-fired boilers for space heating might be used to offset carbon emissions of pumping and treating mine waters. By assuming a CoP of 3, it was shown that CO_2 savings of 0.33 kt per annum might be achievable across Great Britain, yet CO_2 emissions of 10.8 kt resulted from pumping and treatment operations at all sites over the study period. On this basis, the potential for heat recovery from mine waters does not currently offer sufficient carbon savings to offset emissions entailed by mine water pumping and treatment. This is due to the high carbon cost of electricity supply in the UK network, required to supply heat pumps. By using renewable energy resources to power heat pumps, a greater offset would be achievable.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.coal.2016.03.007.

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