NOTTINGHAM TRENT UNIVERSITY

FEASIBILITY OF USING THE WATER FROM THE ABANDONED AND FLOODED COAL MINES AS AN ENERGY RESOURCE FOR SPACE HEATING

Anup P Athresh

B.Eng, M.Sc.

A thesis submitted in partial fulfilment of the requirements of Nottingham Trent University for the Degree of Doctor of Philosophy

February 2017

Abstract

This research project aims to study the feasibility of using the water from the abandoned and flooded coal mines for space heating applications using a Ground Source Heat Pump (GSHP) in open loop configuration and take a conceptual idea to a commercial deployment level. The flooded coal mines are the legacy that has been left behind after the three centuries of continuous operations by the coal mining industry. The closure of all coal mines in the UK has led to the flooding of all those abandoned underground workings and due to the subsequent rise in the water levels; mine water is posing a threat to the water table. Mine water in the abandoned coal mines can be considered as a low enthalpy energy resource with very little practical applications, however it can be upgraded to a high enthalpy resource by using a heat pump and used for heating applications. Heat pumps are considered as low carbon heating systems, using them for the space heating purpose is economically and environmentally beneficial compared to the conventional heating systems.

A generic methodology has been developed to help in evaluating the process of harnessing the energy from mine water for the heating applications using an open loop GSHP. The methodology covers the core technical, environmental and economic aspects. An MS Excel based tool has been developed to assist in the design and commercial evaluation of a mine water based heating system. Financial model is created using Discounted Cash Flow (DCF) method to analyse the feasibility of implementing the system. Theoretical case studies have been conducted for three different sites using the software tool. Two pilot plants have been constructed at two different sites, namely at Markham, Alkane Energy and at Caphouse, National Coal Mining Museum (NCM) for the experimental work.

The field trials from the two pilot plants show promising results in terms of reducing both the operating costs and carbon emissions. It also shows that with a careful design, the threat posed by mine water to the operations and maintenance of the plant can be minimised. The three theoretical case studies conducted show that the energy from the flooded coal mines is a good alternative source for heating and can contribute significantly in reducing the operating costs and the carbon emissions at those proposed sites.

The abandoned mines underlie large parts of UK and at many sites, the water is being pumped out to prevent it from coming in contact with the water table and pollute the water bodies, these sites are ideal to implement the mine water based heating system, as they can support large thermal loads. The energy from the flooded coal mines is ideal to supplement or even replace the conventional sources of heating, as it is reliable and contributes to a reduction in carbon emissions and operating costs. Even though the initial capital costs are higher than other conventional heating systems, it becomes economically feasible with a good payback period, when additional financial incentives in the form of Renewable Heat Incentive (RHI), currently being offered by the government for GSHP technology, is taken into consideration. This research work shows that the energy from the mine water can be profitably harnessed to heat the buildings. The unique design developed to design the system, achieves continuous operation and minimises the maintenance requirements, even when a heavily polluted water is used.

Acknowledgements

I would like to thank my supervisor, Prof. Amin Al-Habaibeh, for his support, guidance and invaluable advice in preparation of this thesis. I would also like extend my sincere thanks to Dr Senthan Mathavan and Dr. Matthew Watkins for the providing me with valuable advice in preparing this thesis.

I would also like to thank Mr. Keith Parker MBE of Alkane Energy for providing me the guidance, support and opportunity at Alkane Energy to develop and test mine water based heating technology.

I would also like to thank Innovate UK (a 2 year Knowledge Transfer Partnership) and Low-Carbon After-Life (LoCAL) project financed by the European Commission, Research Fund for Coal and Steel (Contract No.: RFCR-CT-2014-00001), for providing the funding for this project.

Publication List

Published papers

Athresh, A.P., Al-Habaibeh, A. and Parker, K., 2016. The design and evaluation of an open loop ground source heat pump operating in an ochre-rich coal mine water environment. International Journal of Coal Geology, 164, pp.69-76.

Athresh, A.P., Al-Habaibeh, A. 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. Energy Procedia, 75, pp.1221-1228.

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, pp.1-22.

Athresh, A.P., Al-Habaibeh, A. and Parker, K., 2017. An innovative and integrated approach for using energy from the flooded coal mines for pre-warming of a gas engine in standby mode using GSHP. Energy Procedia, 105, pp.2531-2538.

AL-HABAIBEH, A., MEYEROWITZ, B. and ATHRESH, A., 2015. The Design and Development of an Innovative Simulator for an Open Loop System for Extracting Energy from Flooded Coal Mines. Energy Procedia, 75, pp. 1470-1476.

Accepted papers

Athresh, A.P., Al-Habaibeh, A. and Parker, K., Performance analysis of using mine water from an abandoned coal mine for heating of buildings using an open loop based single shaft GSHP system. Applied Energy

List of Figures

List of Tables

Nomenclature

ΔT	Differential temperature in K.
ASHP	Air Source Heat Pump.
asl	above sea level.
CCTV	Closed Circuit Television.
COP	Coefficient of Performance.
$COP_{heatpump}$	Coefficient of Performance of heat pump.
COP_{system}	Coefficient of Performance of the whole system.
CMM	Coal Mine Methane.
Cp	Specific heat at constant pressure in kJ/K.kg.
GSHP	Ground Source Heat Pump.
EA	Environment Agency.
mbgl	meters below ground level.
$P_{heatpump}$	Thermal power output of the GSHP in kW.
$P_{minewater}$	Thermal power of mine water in kW.
ρ_w	Density of water kg/m^3.
RHI	Renewable Heat Incentive.
$W_{HP\ electrical}$	Electrical work done by GSHP in kJ.
$W_{MP\ electrical}$	Electrical work done by borehole pump in kJ.

Table of Contents

1 Introduction

The demand for energy is escalating worldwide and at the same time the availability of conventional energy resources is depleting. This has led to an escalation in the prices of fuel. Conventional fossil fuels are still the main source of energy worldwide. The use of conventional fossil fuels is contributing to an increase in the carbon emission, which is in turn contributing to the global warming and climate change. The climate change is causing concerns globally; governments around the world are promoting the use of alternative energy sources and low carbon technologies to mitigate the climate change and global warming problems.

The ‘Kyoto Protocol’ adopted in Kyoto, Japan, on 11 December 1997 was the first step towards reducing the greenhouse gas emissions, where countries around the world agreed for an international cooperation for the reduction of greenhouse gas emissions, where non legally binding targets were set on the individual countries to reduce the emissions from the 1990 levels (UNFCCC, 2014). The EU has endeavoured to source 20% of all its overall energy from the renewable sources by the year 2020 and has issued a legally binding directive to the UK to source 15% of its energy from renewable sources by the year 2020 (Directive, 2003). In 2012 UK was ranked 25th out of the 27 EU member states, with only 4.4% of its energy being sourced from renewables (EurObserv, 2011; DECC, 2014a; DECC, 2014b). More recently, the United Nations Climate Change conference held in Paris in 2015 passed the ‘Paris Agreement or ‘COP 21’. This agreement made a resolve to limit the maximum rise in global temperatures to 1.5^{0}C and the member countries are supposed to adopt a legally binding target to reduce the emissions (United Nations Framework Convention on Climate Change, 2015).

In 2009, UK's Renewable Energy Strategy gave a breakdown on how the overall target to source 15% of the total energy from renewables can be met. This report envisages that by 2020, 12% of energy used for heating will come from renewable sources (DECC, 2009; DECC, 2012b).

In the UK, nearly half of all the energy utilised in domestic and commercial buildings is for heating and hot water requirements (DECC, 2013; Department for Trade and Industry, UK, 2007). This costs the UK economy nearly £ 33 billion a year (DECC, 2012a). In order to meets its legally binding carbon emissions target, the government of UK endeavours to use renewable heating sources to provide nearly 12% of all the heating demand by the 2020 (DECC, 2009; DECC, 2012b), currently only 2.8% of the heat generated is from renewable sources (Connor, et al., 2015). Heat consumption contributes nearly a third to the greenhouse gas emissions (DECC, 2012a). It is imperative to use low carbon systems to meet the heating needs and heat pumps could be one possible option (Ground Source Heat Pump Association, 2016a).

Flooded coal mines in UK are a potential source of low enthalpy energy. Utilising mine water for heating can greatly help in meeting the target of sourcing 12% of heating demands from renewable energy.

The industrial revolution and coal mining industry has left behind a legacy of vast underground network of tunnels, roadways and permeable goafs (That part of a mine from which the mineral has been partially or wholly removed), which are now filled with water. When the mines were in operation, the mines had to be kept dry and collected water had to be drained and this was continuously pumped up to the ground level, in order to keep the miners working underground safe. This pumping activity artificially altered the ground water level, but since most of the mines were closed during the last decade of the 20th century, the pumping of water also ceased. Now the water level in those regions which were artificially altered has started to recover to its original levels, posing a threat to the ecology and the environment, as there have been instances where mine waters have breached the water table, to rise just below the surface. In some regions, there have been cases were the surface discharges have taken place polluting the water bodies such as rivers and streams (Banks, et al., 1997; Younger, 2016). The mining communities and towns, which once thrived economically when the mines were in operation are now suffering from a socio-economic crisis and are yet to come to grips of mine closures. Many of these towns also suffer from energy poverty, as they were previously completely dependent on coal for their heating needs, when the mines were in operation; the coal from mine was used for heating. Councils and local authorities are trying to rejuvenate and re-energise the economy of all former mining towns, many of those sites have now been regenerated as brownfield sites, with new industrial, commercial and residential complexes being constructed. The new building complexes need heating and sometimes even cooling as well. Most of these new developments is underlain by the abandoned mine workings which are mostly flooded with waters rising steadily underground. Energy from mine water is ideal to meet the heating demands of the new developments and it links well to the mining legacy of the region.

1.1 Research Question

The rising mine water level in the abandoned coal mines is posing a threat to the environment. Mine water possesses low enthalpy energy and cannot be used directly; at this temperature, it has no useful application. However, using the Ground Source Heat Pump (GSHP), the low enthalpy of mine water in the abandoned coal mines can be upgraded to a higher enthalpy resource and used for space heating. GSHP is classified as a low carbon heating system and has a good potential to be deployed on a large scale and for large thermal demands, offering both economic and environmental benefits in terms of reduced operating cost and carbon emissions. Therefore, there is an opportunity to convert an environmental liability into a revenue generating resource. Whilst the potential for harnessing energy from mine water has been known for some time, only limited information is available regarding the small number of sites that have been built and even less information about the performance of those sites is available. The main reason for the limited number of sites built is due to the apprehensions regarding the quality of mine water and the potential damage that it can cause to the equipment, especially in open loop configuration. This research seeks to address this gap in the knowledge by building a GSHP system in an open loop configuration and take a conceptual idea to a commercial deployment level.

1.2 Aim and Objectives

The main aim of this research is to evaluate the feasibility of using water from the flooded and abandoned coal mines for space heating using a GSHP in open loop configuration and to take a conceptual idea to a commercial deployment level. Stimulate the uptake of this technology by highlighting the economic and environmental benefits of implementing the scheme through this work.

The aim of this research is supported by the following objectives:

1. From literature survey, review the theoretical aspects of coal mining methods, mine water and flooding of the mines. Identify the key parameters, which have an impact on the energy content of mine water and devise a method to estimate the potential thermal energy that can be harnessed from those details.
2. From literature survey, review all the aspects about the heat pumps including the theory behind the working of the heat pump, heat pump types, heat pump components, various modes of operations and different configuration setups.
3. Identify the key parameters required for sizing the heat pump, borehole pump (mine pump) and components like heat exchanger and buffer tank. Develop a generic mine water based GSHP system design based on the peak heat demand.
4. Develop a design and a commercial evaluation tool to design and evaluate a mine water based GSHP system covering technical, economic and environmental aspects.

5. Conduct theoretical case studies for potential sites (Markham, Caphouse and Chatterley Whitfield), covering all aspects including technical, economic and environmental factors.
6. Design and build test rigs pilot plants to conduct experimental field trials at two sites (Markham and Caphouse) with different infrastructure and water qualities.
7. Analyse the data from these field trials, including the maintenance aspects along with the performance.
8. Estimate the potential benefits of using mine water based GSHP in comparison with conventional heating systems and conclude the findings with suggestions.

1.3 Thesis structure

The structure of the thesis is organised into eight chapters to cover the whole aspects, starting from the need for alternative source of energy for heating, literature survey, research methodology, theoretical case studies, experimental work of field trials and the conclusion of the study of using mine water as a potential energy resource.

Chapter 1 presents the need to find low carbon heating systems and how mine water in the abandoned coal mines that are posing a threat to the environment can be a potential energy resource. The aim and objectives are introduced in this chapter.

Chapter 2 looks at the literature concerning the coal mines, coal mine flooding, heat pump theory, components of heat pump system, types of heat pumps, benefits of the heat pump and other auxiliary accessories required for the heat pump. The main parameters affecting the thermal energy content of mine water and a method to estimate the thermal energy content are also discussed here.

Chapter 3 describes the research methodology used in this thesis. The methodology consists of literature survey, theoretical analysis that includes case studies and experimental work which involves design and construction of the pilot plants and field trials.

Chapter 4 presents the design process used in the design of mine water based heating system in an open loop configuration. It mentions a step by step process involved in the technicalities of designing the system and measuring the economic and environmental benefits of using a mine water based heating system.

Chapter 5 presents the theoretical case studies of implementing mine water based heating systems at three different sites. The studies cover technical, economic and environmental aspects of the systems.

Chapter 6 presents the details of experimental work from two sites where the pilot plants are built. The site history, coal geology, the technical details of all the equipment used to setup the plant are all presented in this chapter.

Chapter 7 presents the experimental results from the two pilot plants. This includes the performance and maintenance issues as well. Comparison between the two plants are also given at the end of the chapter.

Chapter 8 summarises the whole thesis and presents the conclusions, suggestions and areas where further work can be undertaken.

1.4 Summary

This chapter has highlighted the need to find alternative sources of energy to overcome the dependence on conventional energy sources and reduce carbon emission. The idea of evaluating mine water as a potential heating resource has been proposed in this thesis. The research question, aims and objectives and the structure of the thesis have been presented here.

2 Literature survey

The use of mine water as an energy resource to heat and cool buildings is not new and it has been used around the world with varying degrees of success. As of 2016 only 28 such schemes have been documented and only 57 % of them were coal mine based (Farr, et al., 2016). The application of heat pumps both air source and ground source for heating is well known, especially in the Scandinavian countries. The heat pump is a low carbon heating device and there has been a renewed interest in this technology lately, as the emphasis is on reducing the carbon emissions. The government of UK is actually encouraging the people to use this technology and is even offering financial incentives, in the form of Renewable Heat Incentives (RHI) to people who use heat pumps for heating. In this literature review chapter, the coal mining techniques, subsequent flooding of the abandoned mines with water are discussed in the first part of this chapter and in the later part of this chapter, the heat pumps, physics and thermodynamics of working of a heat pump, types and different configuration of the heat pumps are discussed.

2.1 Coal Mining

There are two methods to extract coal, Open cut/Surface mining method and underground method. In open cut mining, the coal deposits are reached by removing the surface layers of soil and rock. This method is an efficient way to recovery coal as circa 90% of the coal can be recovered, this method is economical when the coal deposits are close to the surface. If the coal deposits are deeper then, it is economically feasible to extract coal by underground extraction method, where the shafts are sunk underground vertically, sometimes more than 1 km deep to the coal seam and then drilling though the coal seams horizontally via tunnels extracting coal. There two main methods of underground mining:

1. Room and Pillar.
2. Longwall mining.

2.1.1 Room and Pillar

This is the oldest mining method and it involves extracting the coal in a grid like pattern. Tunnels are dug into the seam and the coal is extracted as they move forward to prevent the collapse of the roof of the mine. Pillars of coal are left in-situ, thereby creating a grid like pattern, see Figure 2.1. These pillars could either be left behind once the coal has been fully worked from the seam or in some cases, once the mining works had reached the end of the seam they would work in the backward direction removing the pillars of coal as they moved out of the mine. Removal of the pillars would always cause the roof of the mine to collapse and fill up the void space that was initially created by the roads and paths. Due to the extraction and subsequent disturbance of the geology, the permeability of the ground and hydraulic connectivity between the different seams and mine shafts increases. The collapsing of the roof of the seam partially fills the extracted spaces reducing the permeability of the worked seam, this also increases the permeability of the surrounding rock. When the overlying rock collapses, it creates a zone of fracturing in the rock above. The worked coal seams and the fractured rock above all lead to create sub-horizontal zones of increased permeability. Abandoned mines that used the Room and Pillar method may still contain open roadways extending deep into the seam. Open roadways and workings would obviously create a large increase in the permeability. Subsidence of the overlying rock and the removal the pillars for their coal will have filled the void space left behind by mining. If the pillars were left intact, the abandoned workings might still have open roadways existing within the stratigraphy.

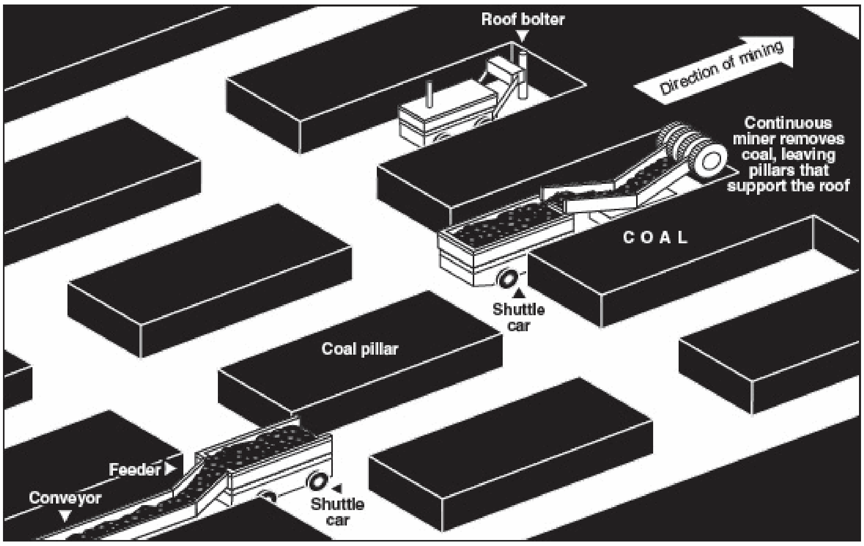


Figure 2.1: Room and Pillar mining operations (Technomine, 2016).

2.1.2 Longwall

Longwall mining is a modern technique that is more commonly used in the newer mines. It involves the use of mechanical shearers to cut through the coal whilst the hydraulic support holds the roof. As the coal is removed, the hydraulic roof also moves forward as the shearer moves deeper into the seam, allowing the roof of the workings to collapse behind the miners, see Figure 2.2. The compete removal of the coal and surrounding rocks creates a subsidence and a large void space is filled in by the falling rock and soil. The void does not get completely filled, as subsidence will never fill more than 90% of the space left, this results in a minimum of 10% increase in permeability (Jamie David Macnab, 2011). This theory is applicable to the Room and Pillar method as well, where the pillars have been removed and the roof collapses into the void left by the worked coal. The increased permeability of the geology improves the hydraulic connectivity and assists mine water, when collected, to flow through the worked seams in abandoned mines.

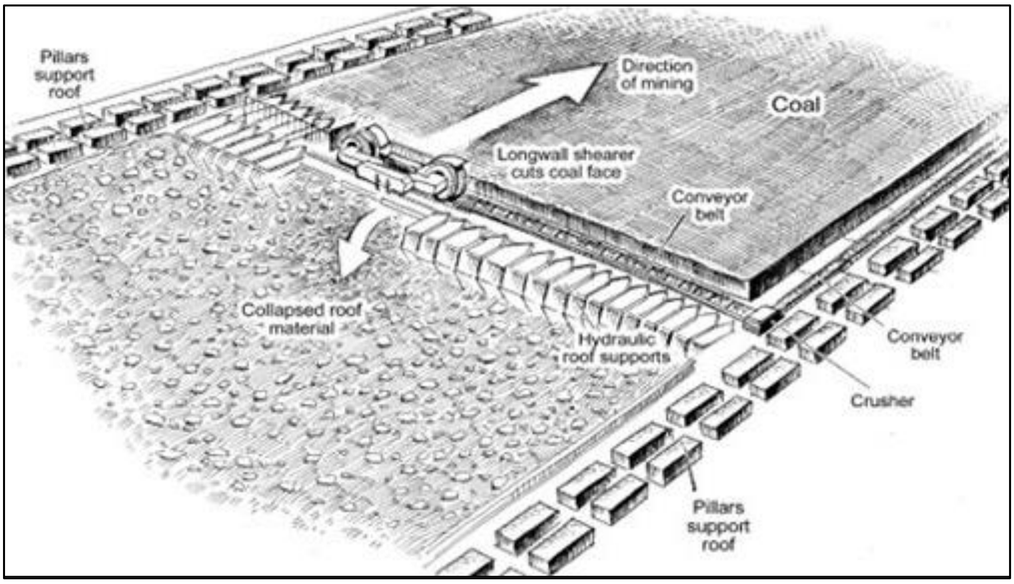


Figure 2.2: Longwall Mining Operations (Earth Science, 2013).

2.2 Flooding of the coal mines and mine water pollution

When the mines were in operation, deep mining of coal involved going further below the water table to extract the coal, this involved continuous pumping of water from the lower geological regions containing the coal seams, this was done to keep the underground seams dry, so that miners could work safely (Younger, 2016). The pumps were placed at strategic locations within and around the mine complex and dewatering caused a disruption to natural hydrogeological conditions (Younger, Banwart and Hedin, 2002). The pumped water was being discharged into the water bodies after removing the suspended particles, iron and other effluents, most often the dewatering operation of an active mine had a big impact on the subsurface hydrogeology

(Younger, 2016). The coal mines in UK and other industrialised nations of Western Europe closed down at the end of 20^{th} century due to economic and political reasons (Younger and Bradley, 1994; King, 1996; Coldewey and Semrau, 1994; Dumpleton, 1996). The closure of the collieries led to the cessation of pumping as well. Cessation of dewatering leads to a gradual recovery of the water level to its initial levels and subsequently filling up the void spaces created due to the extraction of coal with water, this leads to dissolution of efflorescent salts that develop in the drained and ventilated areas due to the pyrite oxidation. This causes deterioration in the quality of water in the abandoned workings after the closure of the colliery (Younger, Arnell and Griffin, 1998; Younger, 1997; Younger, 1993; Younger, 1998; Henton, 1981). The quality of mine water improves but takes a long time (can range from couple of years to couple of decades) (Younger, 1997; Gzyl and Banks, 2007; Wood, Younger and Robins, 1999; Stoertz, et al., 2001). The rising water levels pose a threat to the ground and surface water resources and endanger the local ecology (Henton, 1979; Henton, 1981). There have instances where surface discharge has occurred and has contaminated the rivers (Banks, et al., 1997), fresh water aquifer (Neymeyer, Williams and Younger, 2007) and marine environment (Younger, 2008). In order to prevent mine water from coming in contact with the clean water bodies, the water is still being pumped even after the closure of mines, in UK, there are 64 sites where the water is being actively pumped (Bailey, et al., 2016).

2.3 Mine water as potential of energy resource

Considerable theoretical and academic studies have been carried out to estimate the thermal energy potential of mine water in the flooded coal mines (Rodríguez and Díaz, 2009; Watzlaf and Ackman, 2006; Hall, Scott and Shang, 2011; Kindaichi, et al., 2015; Raymond and Therrien, 2008; Ramos, Breede and Falcone, 2015; Digges La Touche and Preene, 2011; Madiseh, et al., 2012). The mining operations created a vast network of shafts, tunnels and workings underground and since their abandonment; they are now completely filled with water. The temperature of the water is often several ^{0}C above the annual average air temperature. The temperature of the ground at a depth of 100 m in UK is circa 13 – 14 ^{0}C (Banks, et al., 2004).

The usual method to exploit the energy contained within mine water is heat pumps in conjunction with either open or closed loops (Banks, et al., 2004; Banks, et al., 2003). Heat pumps can provide both space heating and cooling. In the winter, the energy is extracted from the water and in the summer, the energy is transferred into the water (Malolepszy, Demollin-Schneiders and Bowers, 2005). The amount of energy recovered will depend mainly on the size and number of heat pumps that are installed. This in turn, is based on the temperature and flow rate of water out of the mine or back into it.

The total thermal power that can be extracted from the flowing mine water is '$P_{minewater}$' in kW is as given below in Equation 1 (Preene and Younger, 2014).

$$P_{minewater} = \rho_w . c_p . \Delta T . q \qquad (1)$$

where ‘q’ is mine water flowrate $m^3\,s^{-1}$, ρ_w the water density and is 1000 kg m^{-3}, ‘C_p’ the specific heat of the water and is 4.18 kJ $kg^{-1}\,K^{-1}$ and Δ T the differential temperature between mine water inflow and return, it is about 5 K for ground source heat pumps (Ordóñez, et al., 2012). Therefore, a peak flow rate of 50 litres per second can serve a peak thermal load of one MW (Preene and Younger, 2014).

When a heat pump is used, it requires energy to a drive compressor, and the efficiency of operation of the heat pump must be taken into consideration. The efficiency of a heat pump is referred to as its coefficient of performance (COP), it is expressed as the ratio of the heat energy delivered to the electrical energy used to drive the heat pumps. The COP delivered by a given heat pump will depend on the relative input and output temperatures (Ochsner, 2012). In normal operation, COP’s vary in the range of 3–6 (Bazargan Sabet, Demollin and Van Bergermeer, 2008).

When the heat pump is used for heating application, the power associated with the motor of the heat pump contributes to heat output $P_{heatpump}$, and is given Equation 2 (Preene and Younger, 2014).

$$P_{heatpump} = \frac{P_{minewater}}{1-[\frac{1}{COP}]} \tag{2}$$

If a heat pump is used to provide cooling, then the thermal potential of the system is reduced due the heat produced in the compressor and is as given in the Equation 3 (Preene and Younger, 2014).

$$P_{heatpump} = \frac{P_{minewater}}{1+[\frac{1}{COP}]} \tag{3}$$

Banks (2004) and Watzlaf and Ackman (2006) document that mine water from both operating and abandoned mines can be used for individual space heating projects, district heating / cooling or for preheating the air for mine ventilation in active mines. Such applications offer the possibility of converting the popular perception of coal mines as an unsightly, potentially polluting environmental liability, to an environment friendly low carbon source of clean renewable energy.

Mine water resource can be classified based on its operating status as: (i) operating (ii) non-operating, but dewatered, for purposes of environmental protection or protection of down-dip working mines and (iii) abandoned mines. In most mines, water enters as infiltration from the surface as groundwater from adjacent, overlying or underlying aquifers or from adjacent older mine workings, or as process water (Hall, Scott and Shang, 2011).

In mining industry most of the subsurface infrastructure (shafts, tunnels, roadways, dewatering pumps, water treatment ponds etc.) required are already built and this reduces the initial capital costs needed for the heat pumps. In an operating mine, this water is usually removed by some form of pumped dewatering operation to prevent the mine from flooding, the energy of the pumped water can be harnessed and used for heating as well as cooling (Ramos, Breede and Falcone, 2015; Jardón, et al., 2013). Many non-operating mines are still being pumped, and will be so for many decades, either to protect still-operating mines or for environmental protection purposes. The Coal authority in UK pumps continuously 3 m^3s^{-1} of water daily (David Banks, 2013; Parker, 2011; Bailey, et al., 2016). The volume of mine water pumped out every day is sufficient to fill 103 Olympic sized swimming pools (patagoniaalliance, 2016). As such, an opportunity to extract energy from these waters, enhancing the economic sustainability of long-term pumping. Water from some of the abandoned mines overflow at the surface, and such uncontrolled discharges are often highly polluting. Other abandoned mines that do not overflow, but they still contain a huge reservoir of subsurface mine water (Jamie David Macnab, 2011).

The potential for the use of underground mines for geothermal applications was first investigated back in the 1980’s (Jessop, MacDonald and Spence, 1995). The first mine water heating scheme was installed at Springhill coal mines, Nova Scotia in Canada (Jessop, MacDonald and Spence, 1995). A pilot plant to provide district heating and cooling to entire town of Heerlen in Netherlands using mine water was installed (Roijen, Op‘t Veld and Demollin-Schneiders, 2007). Following the success of the pilot scheme, the scheme was expanded to a full scale sustainable energy system in the second phase of development (Verhoeven, et al., 2014). The system at Heerlen shows, how a former mining town facing a social and economic crisis following the closure of the mines has successfully managed to transform itself into a modern town based on low carbon sustainable energy using mine water.

Figure 2.3: (a) GSHP unit at Asturias, Spain. (b)Shell and Tube heat exchanger at Asturias, Spain.

Recently at Asturias in Spain, a mine water based heating system has been built on an active mine, where mine water is being pumped out into a river to keep the underground seams dry and safe for the miners to work. Figure 2.3 shows the picture of the heat pump and the shell and tube heat exchangers of mine water based district heating system in Asturias in Spain.

2.4 Heat Pump

The heat pump was invented in 19th century, when the concepts of thermodynamic laws was formulated. It is a commonly visible domestic appliance, refrigerator working in reverse. It is based on the principle of reverse refrigeration cycle of transferring energy that is at lower temperature region (sink) to another region at a higher temperature (source) by means of contribution of mechanical work (electricity). This exchange is achieved with refrigerants, undergoing phase change to a wide range of pressures and temperatures. The thermodynamic process involved are explained later in this chapter.

2.4.1 Thermodynamic principles of heat pump

The principle of operation of heat pumps is not recent. Its origins come from the theory put forward by Carnot in 1824. Lord Kelvin and Clausius R. subsequently developed this concept further.

The Clausius statement of second law of thermodynamics states that it is impossible for the heat to flow from an area of low temperature to an area of high temperature without the aid of an external force. Actual statement of Clausius as stated in his paper (1856) is as follows:

Heat can never pass from colder body to a warmer body without some other change, connected therewith, occurring at the same time.

In the year 1852, Lord Kelvin (William Thomson) had designed a heat multiplier device, which transferred a heat from low temperature surroundings to an enclosed space maintained at higher temperature, using energy (Sumner, 1976). However much earlier in the year 1851, Dr. John Gorrie invented an icemaker in his attempt to find cure for yellow fever (GEORGE L CHAPEL, 2001).

This is obvious from real life experience, when a hand at a lower temperature touches a hot object, the person can feel the flow of heat from the hot object to the hand. It is never the case that the heat flows from the hand to the boiling water. The heat can never flow from a lower temperature to a higher temperature naturally, however, the heat can flow from cold region to hot region with the aid of an external force. Refrigerator facilitates the flow of heat from a cold body, the food inside, to a warmer body, the room or the kitchen, where it is kept. This is possible due to the mechanical work performed by the compressor of the refrigerator powered by electrical energy.

2.4.2 Refrigeration cycle

Robert Irving (2013) has described different types of refrigeration cycles and they have been classified into absorption cycle, gas cycle, Stirling cycle, thermionic, magnetic, Gifford-McMahon, pulse tube, optical, vortex tubes, Vuilleumier and Malone. Only the vapour compression cycle has been discussed here as the two heat pumps used for the experimental work, use them, also most of the commercial heat pump units available in the market use vapour compression cycle.

2.4.3 Heat engine and Heat pump cycle

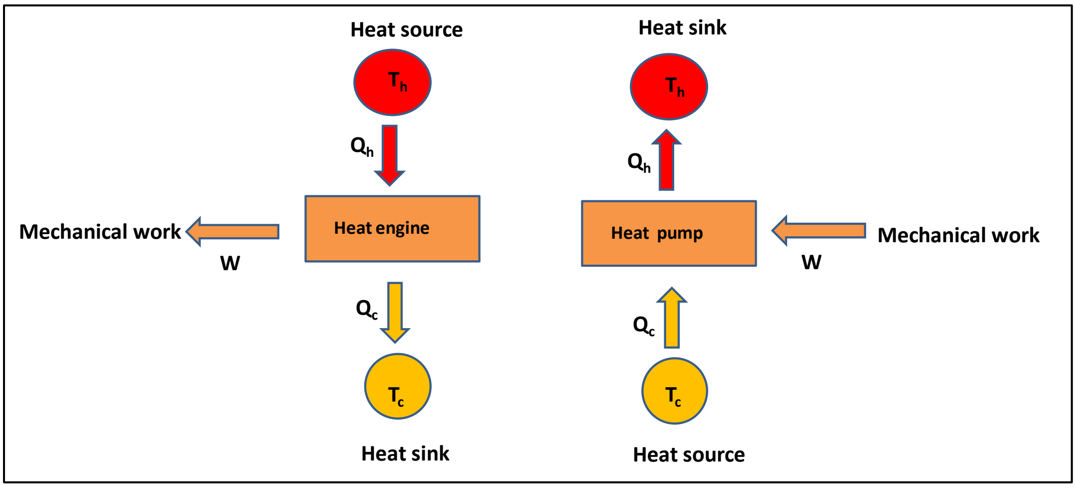


Figure 2.4: Schematic of heat engine and heat pump cycle.

From Figure 2.4, it is visible that the thermodynamic theory of the heat pump cycle is almost the exact reverse of that of the heat engine. In the heat engine, high temperature heat is supplied to perform work as output and residual heat is rejected at low temperature. In a heat pump, the heat is supplied at high temperature from a low temperature region by means of an input of mechanical work.

The energy and work relations for the mechanism is as given below in Equation 4 (McMullan and Morgan, 1981).

$$Q_h = Q_c + W \tag{4}$$

Where 'Q_h' is the heat flow from the source, 'Q_c' 'is the heat flow to the sink, and W is work input. For a heat pump the flows takes place in reverse direction, but the same equation holds good.

For a heat engine, the efficiency, 'η', is calculated as the ratio of the work produced to the heat input as given in Equation 5:

$$\eta = \frac{W}{Q_h} \tag{5}$$

The heat pump can be used for either heating or cooling, calculation of its efficiency depends on the type of application, if the heat 'Q_h', is rejected to the sink in heating mode, or if the heat 'Q_c' is absorbed from the source in cooling mode. This gives two ratios: for heating, $\frac{Q_h}{W}$, the amount of heat rejected for unit work; and for cooling, $\frac{Q_c}{W}$, the amount of heat absorbed for unit work. Rather than the generic term 'efficiency', these values are known respectively as 'Coefficient of Performance' (COP).

$$COP = \frac{Q_h}{W} \tag{6}$$

And 'Energy Efficiency Ratio' (EER):

$$EER = \frac{Q_c}{W} \tag{7}$$

Using Equation 5 and Equation 6 in Equation 4, this gives the following relationship:

$$COP = EER + 1 \tag{8}$$

A heat pump can be used both in heating and in cooling mode. From Equation 8 it can be seen that efficiency of heating mode is higher than that of cooling mode.

2.4.4 Carnot Cycle

The heat engine as defined in the previous section is referred to as a 'Carnot Engine', it is an ideal engine and theoretically has the maximum efficiency. The process by which it works is known as the Carnot Cycle or the 'reversed Carnot Cycle' for refrigeration purpose. This cycle forms the foundation for understanding the functions and restrictions of the vapour compression heat pump cycle. Carnot efficiency is the maximum efficiency that any heat engine cycle can achieve. It follows the laws of physics and it consists of two isothermal processes (constant temperature) and two adiabatic processes (no energy or mass transfer takes place between the system and the surroundings). Carnot cycle is considered as reversible process.

Figure 2.6 and Figure 2.5 represent the ideal Carnot cycle. A—>B and C—>D represent the idealized versions of the condenser and evaporator, where the energy interaction takes place at constant temperature, B—>C and D—>A represent the idealized versions of the compressor and expander and these are adiabatic processes.

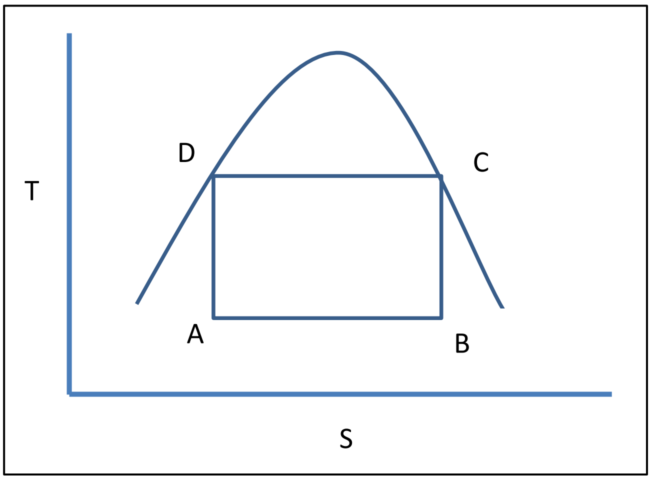


Figure 2.5: Temperature (T) and Entropy (S) diagram reproduced from (Le Feuvre, 2007).

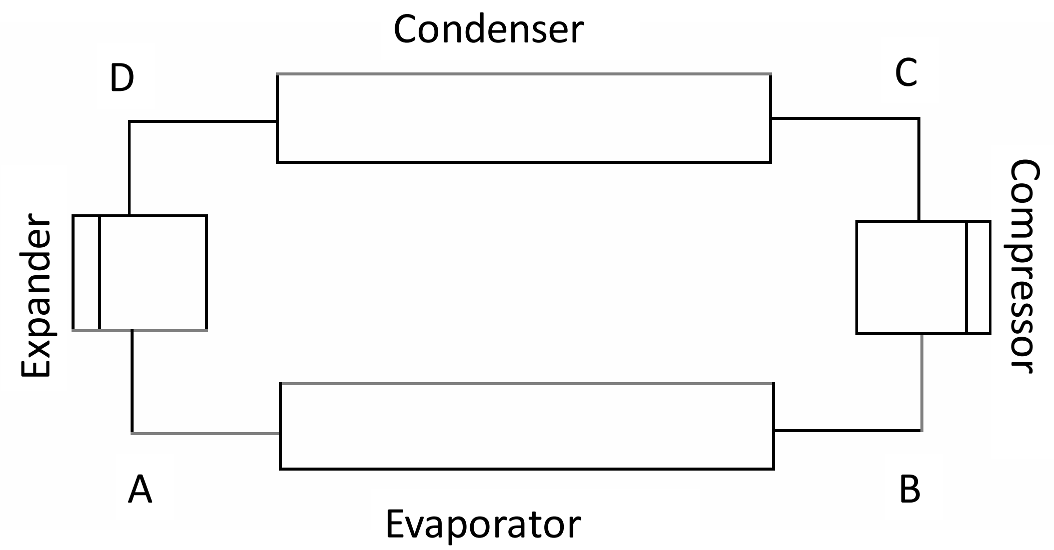


Figure 2.6: Carnot cycle reproduced from (Le Feuvre, 2007).

2.4.5 Coefficient of Performance (COP)

The Coefficient of Performance (COP) measures the level of performance of a heat pump. It is defined as the ratio of the heat output provided to the electrical energy consumed. However, one of the most fundamental factors affecting the COP is the temperature difference between the environments where heat is being transferred from and where the heat is going to. The COP for a heat pump using the ideal Carnot cycle can be expressed as Equation 9 (Sonntag, et al., 1998):

$$COP_{carnot}=\frac{T_H}{T_H - T_L} \qquad (9)$$

Where 'T_L' is the absolute temperature of the cold area from where heat is being extracted from and 'T_H' is the absolute temperature of the hot area from where heat is being transferred to. The Carnot COP represents the maximum theoretical value that can be achieved, in reality the COP will always be less than this due to the losses. It can be seen that minimising the difference between the hot region and cold region will result in an improved COP.

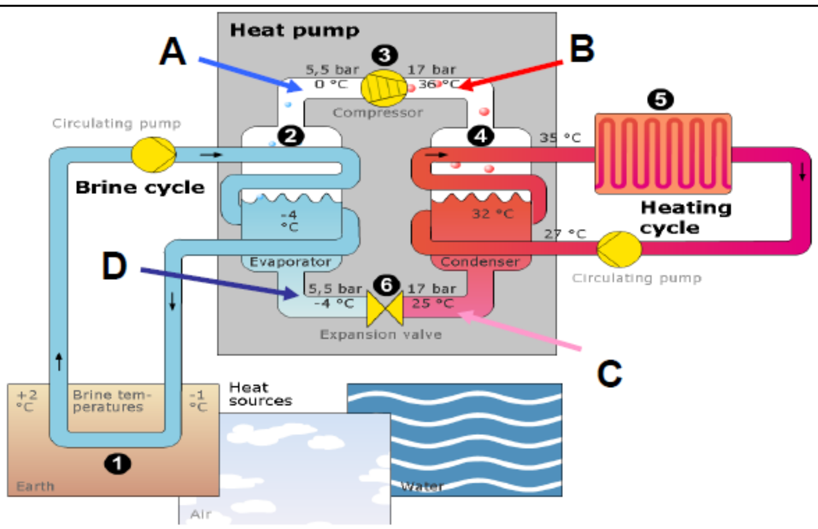
For the real world applications, the efficiency of the heat pump is measured in terms of Coefficient of Performance (COP). It is the ratio of heat output from the heat pump to electrical input to the heat pump, see Equation 10. The COP of a system is always greater than 1 (in terms of efficiency always greater than 100 %). Therefore, heat pump is considered as a low carbon device compared to other conventional gas boilers and electric heaters whose efficiencies at best can be 100%. The UK government is currently running the Renewable Heat Incentive (RHI), a subsidy payment for which ground source heat pump (GSHP) technology qualify. A requirement to qualify for this, the GSHP must have minimum COP of 2.9, conveying the importance set against COP. (OFGEM, 2015).

$$COP=\frac{\text{Heat Output in kJ}}{\text{Electrical Input in kJ}} \qquad (10)$$

2.4.6 SPF

Another useful measure of the performance of a heat pump can be found by calculating the Seasonal Performance Factor (SPF). This is defined as the ratio of the total useful heating provided over a year to the total electrical consumption. This is useful because the COP of a heat pump is not a temporally static figure. Various conditions depending on an Individual heat pump can affect the day to-day and season-to-season COP. The SPF provides a more Insightful measure of how a heat pump is performing under different conditions. (Herold Radennacher, & Klein 1996).

2.4.7 Vapour compression refrigeration cycle of a heat pump



A – Low Pressure COOL Refrigerant GAS
B – High Pressure HOT Refrigerant GAS
C – High Pressure COOL Refrigerant LIQUID
D – Low Pressure COLD Refrigerant LIQUID

Figure 2.7: The refrigeration cycle of a heat pump (Dimplex, 2016).

The working of the heat pump is very similar to the refrigeration cycle, the refrigeration cycle of a heat pump is as shown in Figure 2.7 and it works in following steps:

1. In the evaporator, coolant temperature is maintained below the saturation temperature (sub cool phase) of the heat source, therefore the heat flows from the source to coolant and evaporates the refrigerant.
2. In the compressor, the vaporised refrigerant coming from the evaporator is compressed thereby raising its pressure and temperature.
3. High temperature refrigerant flows into the condenser and the refrigerant is cooled back to its liquid state.
4. Finally, high-pressure liquid obtained out of the condenser expands through the expansion valve until the pressure and temperature drops to the initial level of the evaporator. At this point, the cycle begins again.

2.4.8 Heat pump system components

2.4.8.1 Heat source

The performance and economic benefits of a heat pump are directly dependent on having a stable and reliable heat source. Higher the temperature of the source more efficient will be the heat pump. Air, soil, ground water are the heat sources which are commonly used for small and medium sized domestic and commercial installations, while lake, river, deep geothermal rock and waste water or effluents are suitable for large scale systems, as they are available in large quantities. Mine water is a new addition to the list and is taken as the main heat source for this research work. It is easily scalable to any size and is suitable for both small, medium and large scale units due to the availability of large volumes in the abandoned mines. It has a good potential to be used for district heating as well. Table 2.1 shows the temperature of the various available heat sources.

Table 2.1. Common heat sources (Kärkkäinen and Oy, 2011).

Heat Source	**Temperature range in ^{0} C**
Ambient air	-10 – 15
Exhaust air	15 – 25
Mine water	10 – 20
Ground water	4 – 10
Lake water	0 – 10
River water	0 – 10
Sea water	3 – 8
Rock	0 – 5
ground	0 – 10
Waste water and effluent	>10

Ambient air is available freely and widely. It is most commonly used for air source heat pumps (ASHP). The main drawback of air is that, due to seasonal changes, there is a large fluctuation in temperature. Figure 2.8 shows the seasonal variation in temperature of the ambient air in UK. In the mild and colder climates, as the air temperature decreases, the heating capacity and efficiency rapidly decreases.

Figure 2.8: Variation of air and ground temperature (Le Feuvre 2007).

Exhaust air most of the large buildings generate large amounts of heat in the exhaust of their ventilation system. This hot air is a good source and is suitable to be used for space heating and to produce hot water, using an Air Source

Heat Pump (ASHP). For this system, the ventilation system needs to be running all the time. This system is most often used in conjunction with a conventional heating system.

Ground Water, the temperature of the ground increases as we go deeper into the ground. It increases by 1 to 3 ^{0}C per 100 m in most of the tectonically stable areas (Banks, 2012). The temperature of the ground water is not affected by the ambient temperature and it remains constant throughout the year irrespective of the season. The heat can be extracted either by open or closed loop systems. The water can be directly used in the heat pumps through an open loop system, but careful consideration has to be given while discharging the water so as not to affect the water table. If the water has any impurities, an intermediary heat transfer fluid or brine can be circulated in a closed loop configuration, thereby preventing any damages to the system due to corrosion. The main disadvantage of this system is the higher installation costs involved in drilling and groundworks and additional environmental regulations for the extraction and discharge of the water, which has the potential to pollute the water table.

Ground Source systems, here the temperature of the ground rather than ground water is used as heat source and heat from the ground is extracted by passing the refrigerant/brine (heat transfer fluid) through the closed loop which can be inserted either through vertical loops or horizontal loops. Both, brine system in conjunction with a heat pump or direct expansion system without a separate heat pump unit can be used.

Rock, in regions where not much ground water is available, the geothermal rocks underground is at a higher temperature and can be used by sending the heat transfer fluid through them and pumping a hotter fluid back. Only open loop can be used in this case. For a large heat capacity, multiple boreholes need to be drilled, as a large rock volume will be needed to extract the large amounts of heat.

River and Lake have large volumes of water and are ideal for large scale systems. Lakes and rivers water is generally clean and should not pose any corrosion issues. The main disadvantage is that the temperature is slightly lower and is affected by seasonal fluctuations, in winter the temperature of the water can reach 0 ^{0}C, thereby freezing the evaporator. There is always a possibility of some fauna being killed if it gets into the pump (in open loop condition).

Seawater is a good source of heat and can meet the demands for a large heat loads. Due to a high concentration of dissolved salts and constant temperature between 3 to 8 ^{0}C, there is very little chance of freezing. The high concentration of dissolved salts can cause corrosion problems and marine fouling. An open loop system with an intermediary heat exchanger will be required. The heat exchanger materials that can withstand marine water will be needed and this will increase the costs. Similar to river and lake systems there will always be a potential of marine animals and plants getting into the system.

Wastewater and effluent, industrial effluents, power generation, sewers (both treated and untreated), cooling water from the industrial process etc. are excellent sources of heat and can match higher heat loads demanded by a large user. The effluents are a source of constant temperature and are available throughout the year.

Mine water, potential of mine water as a heat sources is the central idea in this thesis and its suitability has been discussed earlier in this chapter.

2.4.9 Heat pump components

2.4.9.1.1 Compressors

The compressor is the most important part of a heat pump system and can be called as the 'heart of the heat pump'. The compressor consumes the maximum electricity given as input and is therefore important to choose the one that has the maximum efficiency. The ratio of absolute discharge pressure to the absolute suction pressure is known as the compression ratio, lesser the ratio, lesser will be the power required as less electricity will be needed. Introduction of the scroll compressors (fitted on most of the modern heat pumps) has made a big impact on improving the efficiency, as it can be seen from Figure 2.9. A scroll compressor is hermetically sealed and consists of two interleaved spirals and one of them moves eccentrically with respect to the other. The compression due to the eccentric movement of the moving spiral, compressing the incoming fluid and discharging the fluid at higher pressure. Unlike the reciprocating compressors, the scroll compressor has fewer moving parts, is maintenance free and has very little noise (Omer, 2008).

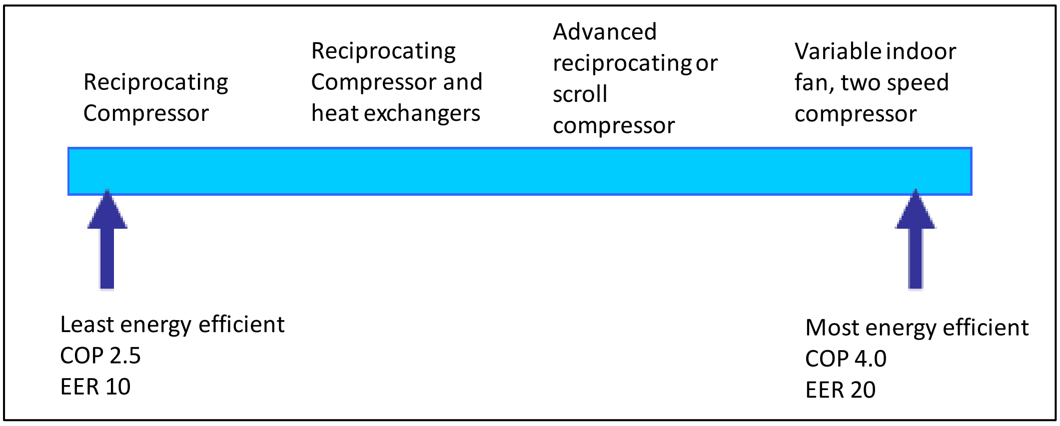


Figure 2.9: The comparison of the compressor efficiency reproduced from (Omer, 2008).

2.4.9.1.2 Accumulator

The main function of the accumulator is to maximise the performance of the heat pump. Compressors are meant to compress only the vapours and not liquids, during the compressing process, if any excess liquid is returned to the compressor, it could potentially cause the dissolution of the compressor lubrication oil and any loss of oil will lead to wearing of the bearings. The accumulator acts as reservoir, traps the cool low pressure refrigerant, and allows the liquid refrigerant to evaporate before the refrigerant enters the compressor. The accumulator is usually located before the compressor.

2.4.9.1.3 Control system

Most of the modern day heat pumps are intelligent devices and are controlled by a programmable micro controller, which reacts quickly to any changes in demand and supply parameters to give a desired output or operate only when necessary to take advantage of off peak electricity prices. They also store data that are helpful for diagnostic purposes and allow for remote monitoring and control.

2.4.9.1.4 Refrigerant

It is the working fluid that circulates around the compressor, evaporator and condenser, undergoing phase changes absorbing heat during the evaporation phase and giving up the heat during condensation phase. It is therefore required to change phase at 'useful' temperatures and pressures. The evaporation cycle is particularly important since incomplete evaporation can cause ingress of fluid into the compressor, which is undesirable mechanically (Reay and Mac Michael, 1986). The refrigeration fluid must be heated beyond the normal evaporation temperature (superheated) within a safety margin. ‘Any fluid which can be made to evaporate between 1 bar and 20 bar at useful temperatures is interesting' (Reay and Mac Michael, 1986). The desirable characteristics of refrigerants are as follows (Reay and Mac Michael, 1986):

- Have a low boiling point, so that it can evaporate quickly.
- Low toxicity for handling.
- Low flammability.
- Inexpensive.

2.4.9.1.5 Electrical requirements

The heat pumps are powered by an electric motor and therefore draw large current initially at start up due to inductive load. The distribution network should have sufficient capacity to withstand the load, without causing any voltage surges, flickering of light or prematurely damage main fuse. The electricity supply regulations 1988, has specified the limits of voltage variation due to switching on and off. The voltage variation is dependent on impedance as given in Equation 11 (Le Feuvre, 2007).

$$Z=R+jX \tag{11}$$

Where, Z is impedance, R is the resistance and X is reactance.

In order to limit the voltage variation, the following steps can be taken (Ground Source Heat Pump Association, 2007):

1. Have a soft starter to spread the load on start up.
2. Have a low torque compressor.
3. Auxiliary system to limit starting current to the heat pump system.
4. Whenever possible go in for a 3 phase supply and motor.

2.4.9.1.6 Auxiliary heater

Most of the modern day heat pumps come with an auxiliary heater, which will step in if for any reason the heat pump fails or is not able to cope with the demand. Heaters can come directly attached with the heat pump unit or as standalone unit, but controlled by the heat pump.

2.4.9.1.7 Reversing and Check Valves

Some of the heat pump models can be used for heating in winter and cooling in summer by reversing the direction of the refrigerant flow by a Reversing Valve. They can be actuated via a four-way solenoid valve to interchange the functions of the evaporator and condenser.

2.4.9.2 Buffer Tank

A buffer tank stores the hot water produced by the heat pump. It is placed between the heat pump and the hot water distribution system. The heat demand from the building side is not always constant and is highly variable depending on the ambient temperature. Even if the temperature in the distribution system reaches the set temperature, the heat pump can continue its operation and fill up the buffer tank. The buffer tank helps to even out the demand and supply requirements and prevents the cycling of the compressor, thereby preventing premature failure of the compressor.

The calculation of the size of the buffer tank is given below in Equation 12 (homemicro, 2016):

$$t = \frac{m.C_p.\Delta T}{Q} \qquad (12)$$

Where ‘t' is time in seconds (operating time of 10 minutes to heat the tank), ‘C_p’ specific heat of fluid, ‘ΔT’ is the difference in flow and return temperature, ‘Q’ is the peak thermal output of heat pump. ‘m’ is the mass in kg.

2.4.9.3 Heat Exchanger

Mine water can sometimes contain particles and ions that can corrode the pipelines and filters. In open loop configuration, if the raw mine water is used directly in the heat pump, the internal parts of the heat pump can get corroded. In order to prevent this from happening a prophylactic heat exchanger is used where a brine solution extracts the heat from mine water and circulates around the heat pump. If any problems of corrosion or clogging occurs, it would be isolated at the heat exchanger only and not the whole system. Hence, the cost of maintenance and break down are also significantly reduced.

Mainly two types of heat exchangers are used as prophylactic heat exchanger and they are:

1. Plate heat exchanger.
2. Shell and tube heat exchanger.

2.4.9.3.1 Plate heat exchanger

Plate Heat Exchangers, using a series of stacked plates and hot and cold fluid pass between the plates transferring heating from hot fluid to the cold fluid, see Figure 2.10. Plate heat exchangers are usually brazed or gasketed depending on the application and fluids being used, in the gasketed type the plates can be removed to clean. The plate heat exchanger offers better heat transfer rate and occupies less area. The main problem is that if it gets blocked due to any contaminants, it is not easy to clean.

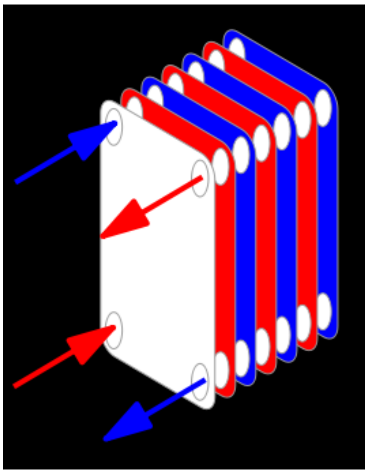


Figure 2.10: Plate heat exchanger (Malyszkz, 2011).

2.4.9.3.2 Shell and Tube heat exchanger

Shell and Tube Heat Exchangers consist of a large number of small tubes that are inserted within a cylindrical shell. The tubes are positioned into the cylinder using a tube bundle, one fluid flows inside the tubes and the other fluid flows over the tubes, but inside the shell. The heat transfer takes place from the hot fluid to cold fluid, see Figure 2.11. Various configurations of shell and tube heat exchangers available. The shell and tube heat exchanger requires a larger footprint and is more expensive. It is much easier to clean them.

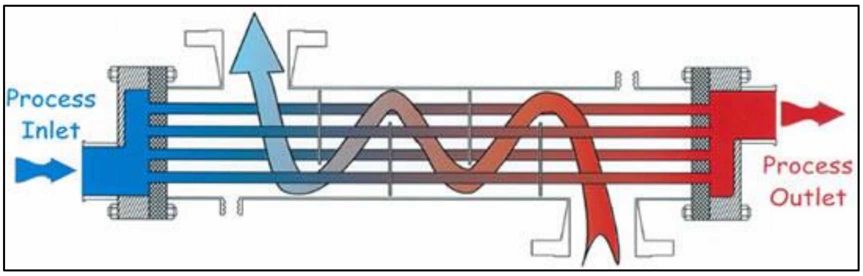


Figure 2.11: Shell and Tube heat exchanger (Southwest Thermal Technologies Ltd., 2016).

2.4.10 Distribution systems

As it can be seen from Figure 2.12, the temperature of the hot water plays an important role in the efficiency of the heat pump. Higher the source temperature, higher will be the efficiency of the heat pump. Lower the hot water output temperature, higher will be the efficiency. This is because the increase in the temperature differential between the source and hot water requires more energy, thereby leads to a decrease in the efficiency.

The temperature of the source is independent and cannot be controlled; only the hot water temperature can be controlled. From the Figure 2.12, it is clear that having low temperature emitter system is necessary to achieve a higher efficiency. Table 2.2 shows the temperature requirement for the different emitter systems. Conventional radiator systems have a flow and return temperature of 90 – 60 ^{0}C and are not suitable, especially when retrofitting a heat pump instead of a gas boiler. The radiator area will have to be oversized to the increase the surface area to compensate for the loss in hot water temperature.

The selection of the distribution system is important, if they are undersized, large demand will be placed on the heat pump and it will run for a longer duration without stopping. If it is oversized, the heat pump will run for a very short duration frequently and might prematurely wear the compressor. Having a restart timer delay and buffer tank to store the hot water and circulate it only when necessary will prevent the cycling of the compressor of the heat pump.

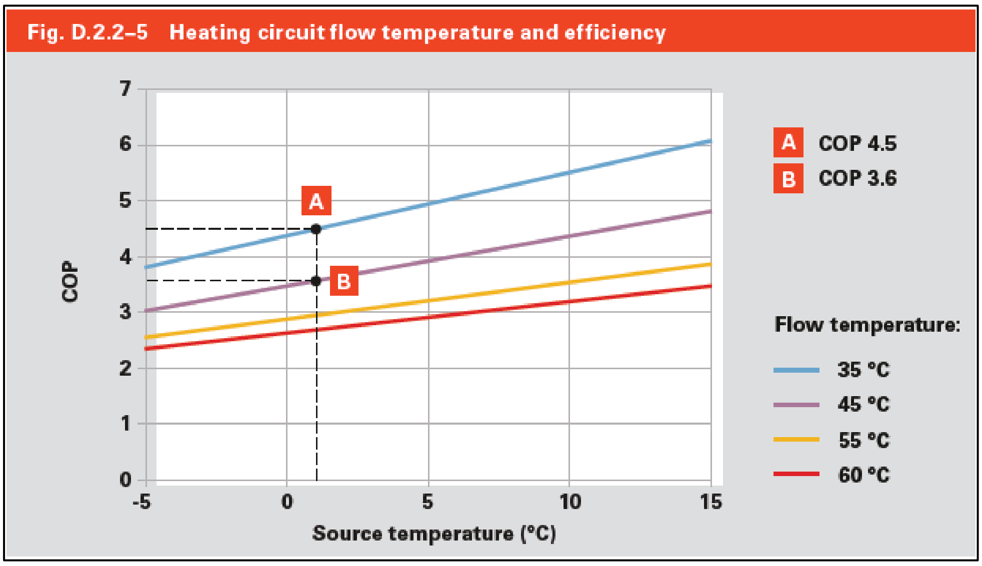


Figure 2.12: Hot water temperature and efficiency (Viessmann UK, 2012).

Table 2.2: Emitter hot water temperature requirement. (Ground Source Heat Pump Association, 2007).

Distribution system	**Delivery temperature in ^{0}C**
Underfloor heating	30 - 45
Low temperature radiators	45 - 55
Conventional radiators	60 - 90
Air	30 - 50

2.4.11 Benefits of a heat pump

The heat pump cannot be classified as a 100% renewable energy device like a wind turbine or a solar panel, unless the heat pump is powered by a renewable source. Heat pumps have an efficiency of 300% to 600% (COP of 3 to 6) and are considered as low carbon devices, as it gives more in output than it consumes as input and significant portion of its energy comes from renewable sources like ground, air or water (eg. If a heat pump gives 4 kW of heat and has a COP of 4, 1 kW comes from electricity and 3 kW comes from renewable source). Higher the efficiency, higher will be the renewable part in the output.

2.4.11.1 Carbon emissions and operating cost

Since the heat pump is a low carbon heating device, the operating cost per unit of thermal energy produced and carbon emissions per unit of thermal energy produced are the least, when compared with the traditional energy systems like oil, gas and electricity based heaters. Figure 2.13 shows the cost and carbon comparison between different heating technologies, costs and carbon emissions are at least 30 % lower than the fossil fuels. The initial capital costs of a heat pump are much larger, but in the long term, it is economically very attractive, as there will be significant savings in the operating costs. Additionally, UK government offers additional financial benefits in the form of Renewable Heat Incentives (RHI). Currently a domestic heat pump receives £ 0.1933/kWh (OFGEM, 2016a) and commercial system receives £ 0.0895/kWh for every kWh of heat produced by the GSHP (OFGEM, 2016b).

The energy from heat pumps are reliable and offer energy security, unlike the solar and wind systems which cannot be considered reliable, as on a cold winter evening, when the demand for the heat is maximum, there will be no generation from solar panels and if there is no wind there will be no wind power as well. GSHP’s were estimated to be saving circa 5.5 million tons of carbon by the end of 2012 in Europe (Bayer, et al., 2012). A heat pump has been estimated to save between 31% to 88% of carbon emissions during it's lifecycle of 20 years in Europe depending upon the regions within the continent on space heating in comparison to conventional heating devices (Saner, et al., 2010). Not only in Europe but also in warmer climates like India significant reduction in electricity and carbon emissions can be achieved, if the heat pumps are used for space heating and cooling (Sivasakthivel, Murugesan and Sahoo, 2014; Sivasakthivel, Murugesan and Sahoo, 2012).

Table 2.3: Operating cost comparison (Dimplex 2016).

Heating Type	Typical Efficiency	Typical Fuel Unit Cost (p/kWh)	Cost per kWh delivered (p)**	Running cost for 15,000kWh/yr (£)
Condensing Gas Boiler (A	**90%**	**3.06**	**3.40**	**£510.00**
Existing Gas Boiler	80%	3.06	3.82	£573.00
Condensing Oil Boiler	90%	5.8 (60p/litre)	6.44	£966.00
Existing Oil Boiler	80%	5.8 (60p/litre)	7.25	£1087.00
Electric storage heating	100%	5.37	5.37	£805.50
Heat pump (worst case scenario)	250% (CoP 2.5)	8.16*	3.26	£489.00
Heat pump (good scenario)	300% (CoP 3.0)	8.16*	2.72	£408.00
Heat pump (better scenario)	350% (CoP 3.5)	8.16*	2.33	£349.50
Heat pump (best case scenario	**400% (CoP 4.0)**	**8.16***	**2.04**	**£306.00**

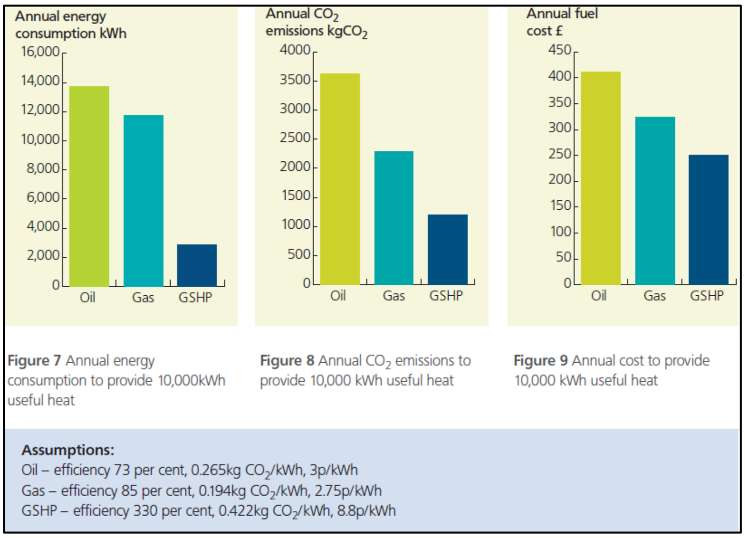


Figure 2.13: Comparison of different technologies (Ground Source Heat Pump Association, 2007).

Other benefits of the heat pumps include:

- Very little maintenance cost.
- No pollution, as harmful gases are not produced.
- No ventilation or flue gas requirements.
- Long term energy stability and reliability.
- Ideal for district heating as well.

2.5 Operation mode

In order to achieve maximum efficiency, it is imperative to size the heat pump appropriately. The heat pump can be run in four different modes and they are:

- Mono mode.
- Dual mode.
- Combination mode.
- Cascade mode.

Each of these modes are described in detail below.

2.5.1 Mono mode

In this mode, the heat pump acts as the sole heat source and covers the entire heating demands of the building. The maximum system temperature will be equal to the maximum flow temperature that a heat pump can achieve. This mode is suitable for the low temperature systems with the maximum temperature being limited to 60 ^{0}C.

2.5.2 Dual mode

In the dual mode apart from the heat pump an additional heating source is used either to meet the additional heating demand or to achieve the higher temperate that heat pump cannot meet. The additional heating source can be an electric heater, oil, gas or biomass boilers. The additional heaters can work either in parallel or simultaneous mode.

2.5.3 Cascade mode

In a big commercial or office setting, different regions might have different heating needs and in order to meet the customized heating needs, the heat pumps are used in cascade mode, where multiple heat pump units are combined, where a master unit controls the slave units.

2.6 Heat pump in cooling mode

Heat pumps have been used for cooling purpose as well. Traditionally, heat pumps were the chillers that were used in reverse for heating, but the modern heating needs are not suitable to convert the heating only heat pump to heating and cooling systems. Following points need to be considered when using a heat pump in cooling mode (Langley, 2002).

1. Additional surface area is required for emitter to prevent excessively high condensation temperature.
2. Compressor should be able to work all year round and at different pressure conditions.
3. Sufficient flow will be required for the air distribution systems to ensure condensing of the refrigerant.
4. In air source systems, a defrost cycle will be needed to prevent freezing.

Cooling can be accomplished either in passive mode without running the heat pump or in active mode, where the heat pump provides the cooling effect.

Care must be taken to prevent the surface temperature of the emitter from falling below the dew point to prevent condensation on the surface of the emitter system.

2.6.1 Active cooling

The vapor compression heat pump can be used not only for heating, but can be operated to run in cooling mode as well, by reversing the flow of the brine and by interchanging the functions of condenser and evaporator. By using the heat pump in cooling mode in summer and in heating mode in winter, the use of the heat pump is maximised. If the heat pump is using ground as primary heat source, then the heat removed from the building during the summer will be stored in the ground and will be used for heating during winter. See Figure 2.14. A 4-way valve will be needed to reverse the flow direction of the refrigerant, while the compressor continues to operate unchanged.

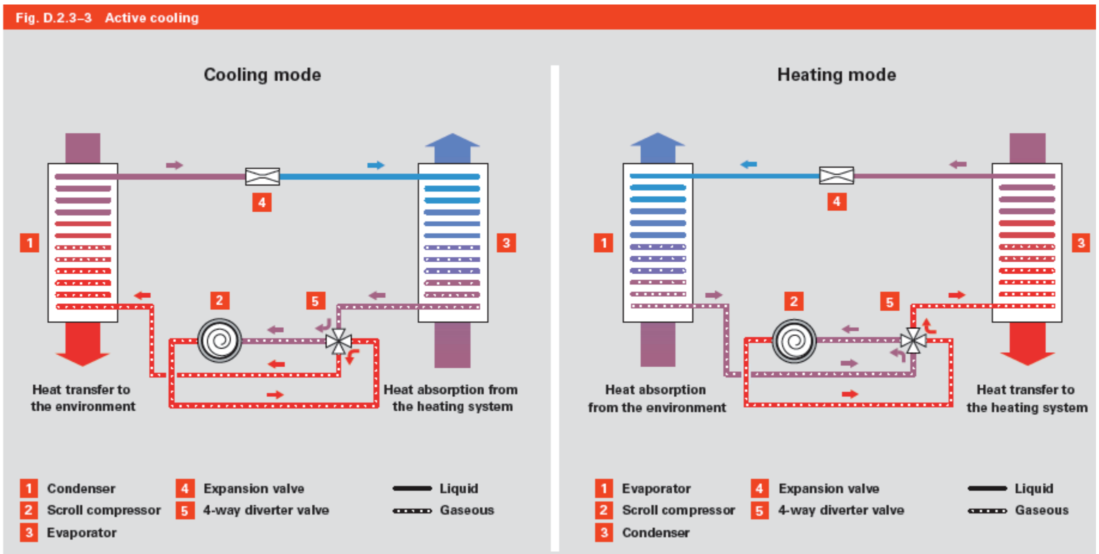


Figure 2.14: Schematic of active cooling (Viessmann UK, 2012).

The cooling capacity of reversible heat pump will be less than the heating capacity because in the heating mode, additional heat is produced during the compression will also be added to the hot water, while in cooling mode this will not be used, the COP of the cooling mode will also be less due to the energy spent in removing the additional heat.

2.6.2 Passive cooling

In summer, the temperature of the ground will always be lower than the temperature inside the building and this differential temperature that exists between building and the ground can be utilised to achieve cooling. Additional heat exchanger, 3-way valve and circulation pumps are needed, see Figure 2.15. The water is circulated around the house and it removes the heat through the emitter system. Very high COP value can be achieved; as only small amount of energy will be used by the circulation pump.

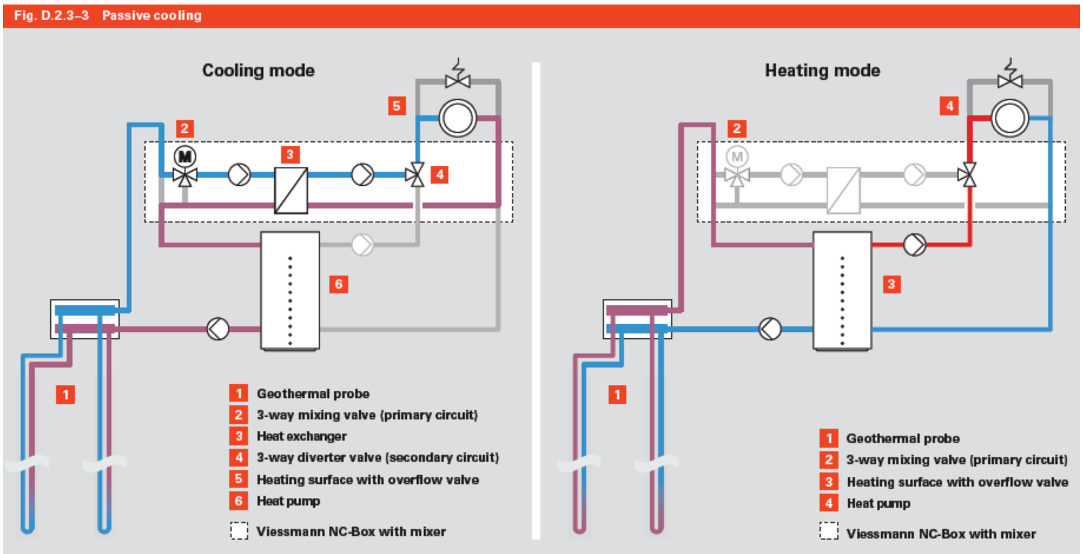


Figure 2.15: Schematic of passive cooling (Viessmann UK, 2012).

2.7 Types of Heat pumps

Based on the type of the fluid (either air, water or brine) used to source the thermal energy from, the heat pump is classified as either Air Source Heat Pump (ASHP) or Ground Source Heat Pump (GSHP). In ASHP, heat exchangers are exposed to the outside environment and they extract heat from the ambient air. GSHP consist of heat exchangers, which are buried in the earth and extract the heat stored in the soil and rocks or from the water underground. This research work focuses only on the use of GSHP, where the energy stored in the underground mine water instead of normal ground water.

2.7.1 ASHP

The schematic of an ASHP is as shown in the Figure 2.16. The energy from the ambient air is extracted and used for space heating. ASHP are more efficient that conventional boilers. Even when the air temperature is as low as -15 ^{0}C, ASHP can be used, however their efficiency will be lower. Figure 2.17 shows the variation in air temperature in UK during winter, the time when the maximum heat is required, the ambient air temperature is low. Figure 2.18 shows how the COP of the ASHP decreases with the increase in air temperature.

Table 2.4: Advantages and disadvantages of ASHP

Advantages of ASHP	Disadvantages of ASHP
Less capital costs.	Not suitable for bigger thermal loads in excess of 1 MW.
Requires less footprint.	Less efficient, due to large variations in ambient air temperature throughout the year.
Simple in design.	More operating costs.

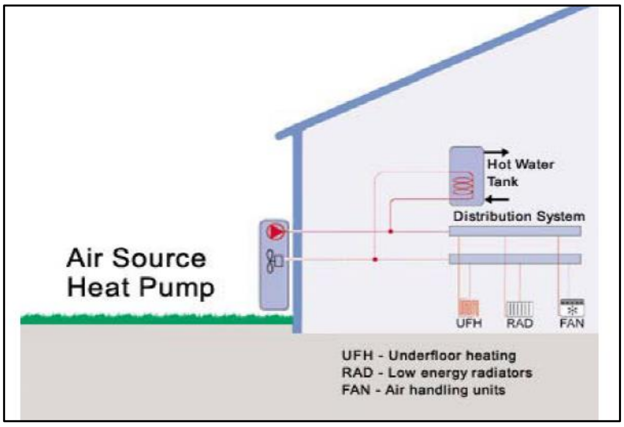


Figure 2.16: ASHP (Econis Rewnewable Energy Solutions, 2010).

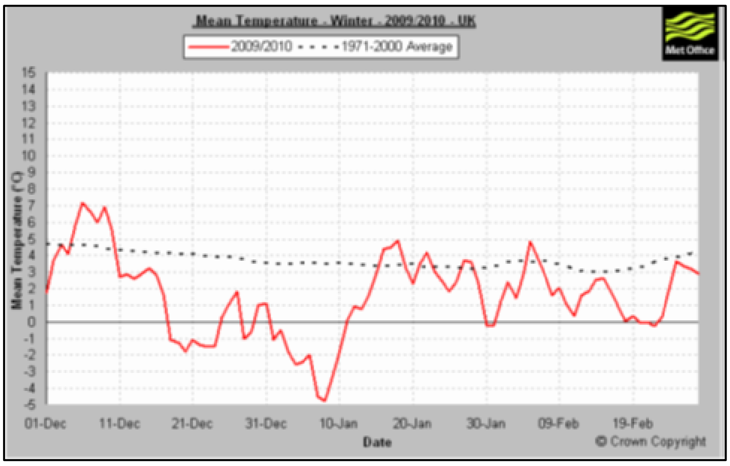


Figure 2.17: The winter ambient air temperature UK (The Met office, 2010).

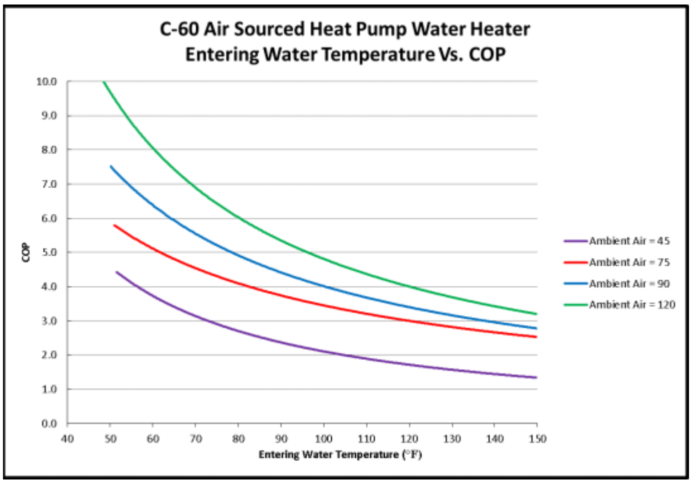


Figure 2.18: The COP variation with ambient air temperature (Matthiessen T, 2011).

2.7.2 GSHP

The energy is extracted from the soil or from water underground, by circulating a heat transfer fluid or the water from the water table, through the pipes that are laid horizontally or vertically. Figure 2.19 show the annual variation in air and ground temperature, it is clear that the temperature variation reduces, the deeper we go underground. There is very little variation in the temperature between winter and summer. Therefore, since the source temperature is constant, a higher COP can be achieved in GSHP. Water has a high convective heat transfer coefficient of circa 1200 $Wm^{-2}K^{-1}$ (EngineersEdge, 2016), when it is flowing in a tube. While the air has a convective heat transfer coefficient of 100 $Wm^{-2}K^{-1}$ (EngineersEdge, 2016) (air travelling at a moderate speed over a surface). Therefore, the GSHP's can have a heat transfer coefficient of at least 12 times more than those of ASHP.

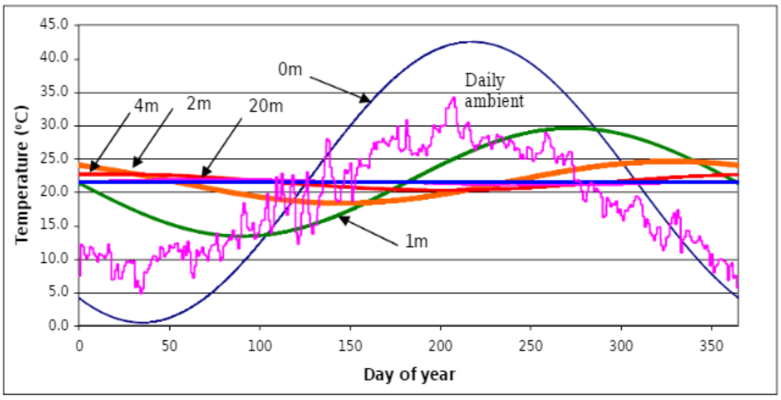


Figure 2.19: Annual air and ground temperature variation in Cyprus (Florides and Kalogirou, 2005).

Table 2.5: Advantages and disadvantages of GSHP.

Advantages of GSHP	Disadvantages of GSHP
Higher COP, due to a stable ground temperature throughout the year	Requires more foot print

Less operating cost	Higher capital cost due to drilling and pipe material
Can meet bigger thermal loads of more than 1 MW	Design is more complex
Suitable for district heating	Requires Environmental Agency permits

2.8 Classification on GSHP systems

The GSHP systems that extract energy from the ground or the underground water are further classified as:

1. Open Loop system.
2. Closed loop system.

Several factors have to be considered when selecting the right system for a specific installation: Geology and hydrogeology of the underground (sufficient permeability is a must for open systems), area and utilization on the surface (horizontal closed systems require a certain area), existence of potential heat sources like mines, and the heating and cooling characteristics of the buildings. In the design phase, it is necessary to size the ground system in such a way that optimum performance is achieved with minimum cost. The individual types of GSHP systems are described in more detail below.

2.8.1.1 Open loop system

Open-loop heat pumps involve the direct abstraction of water from the source and passing through a heat pump or through an intermediary prophylactic heat exchanger between the heat pump and the water. Since there is no barrier between the rock/soil or water and the heat pump, it is called open system. A suitable aquifer is required such that there is a reliable and usable volume of water available. Also, if the spent water is not utilised or cannot be discharged suitably on the surface, a rejection borehole might be required to dump the spent water, see Figure 2.20. The design component of the extraction well, requires planning for the depth of the well, as the depths of aquifers range from a few meters to 100’s of meters below the surface, the diameter of the well constrains the size of the bore pump which can be installed and hence the yield from the well. It also requires a through geotechnical study of the site that needs to be drilled. There is also additional power consumption arising from the pumping of the water from depth (Athresh, Al-Habaibeh and Parker, 2015).

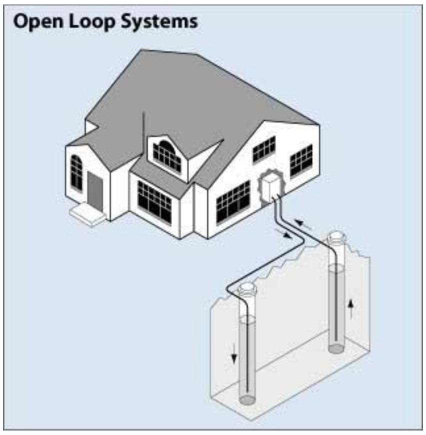


Figure 2.20: Open Loop GSHP system (BGS, 2016).

In the direct system, a warmer water is pumped directly from the source and passed through the heat pump and then returned to the source at a lower temperature. These offer high efficiencies as they do not require an intermediate heat transfer carrier, the heat is transferred directly from the water to the refrigerant of the heat pump. The lack of requirement for this intermediate stage reduces the capital cost of the system and simplifies the design. Care must be taken depending on the conditions of the water that is being pumped into the heat exchanger of the heat pump. A filtration system may be needed to protect the heat exchanger of the heat pump from the damaging debris. This increases the maintenance requirements and power consumption. The water quality has to be thoroughly analysed to prevent clogging problem anywhere in the system.

If the water quality is not good, then having a prophylactic heat exchanger is necessary between the heat pump and water, so that if there are any clogging or contamination, the problem can be isolated only to the less expensive heat exchanger and prevent any damages to the more expensive heat pump unit.

In this research work, mine water, which is present in abundance in the abandoned mine workings is used as a source and a prophylactic heat exchanger is also used to eliminate any potential damage to the heat pump.

The earliest open loop GSHP system was installed in Norwich, UK in the year 1948 by an Electrical Engineer called John Sumner (Sumner, 1976). The GSHP used the water extracted from the River Wensum to heat the building. The heat pump had a peak thermal output of 234 kW (147 kW average thermal demand) and was constructed using the salvaged parts, see Figure 2.21. The GSHP had an average COP of 3.45.

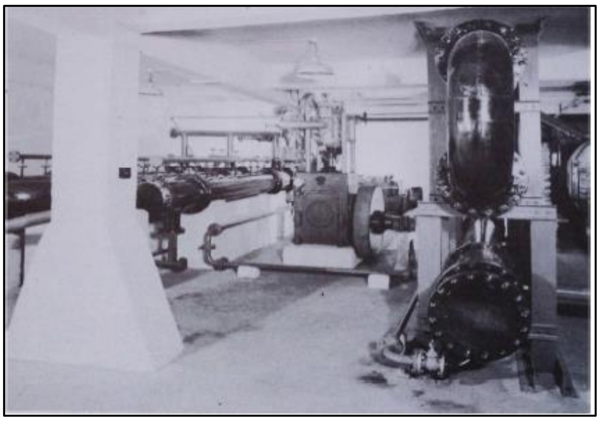


Figure 2.21: John Sumner’s Norwich GSHP (Sumner, 1976; Banks, 2012).

2.8.1.2 Closed loop system

These use Intermediate heat transfer fluid to transfer heat directly from the water source or earth. This involves the use of an intermediate fluid that is commonly an antifreeze solution, although it can be a variety of chemicals including ammonia and glycol. They are generally installed as either horizontal or vertical loops, their environmental interaction is limited to the water being exposed to these loops. However, the intermediate fluid if leaked can have potentially damaging effects. Their design is primarily specified by the properties of the body of water they are to be used with, the design generally requires less maintenance than an open-loop system. The closed loop has been further classified based on the configuration of the loops and they have been described below.

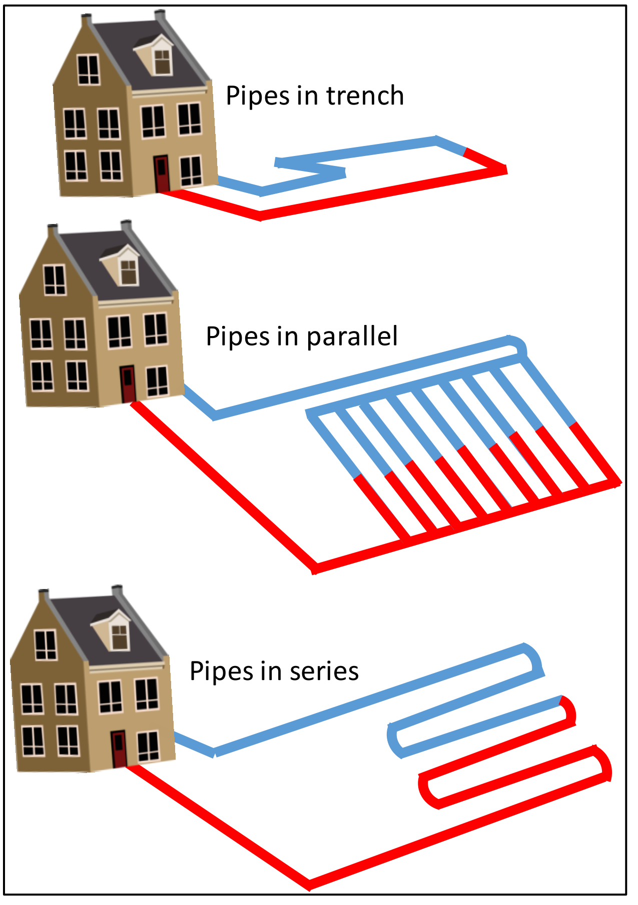
2.8.1.2.1 Horizontal loop system

The top layer of the earth is removed and the pipes are laid in the ground at a depth of 1.2m to 2m below the surface. The removed soil is distributed back over the pipes. To save large surface area from being removed for ground heat collectors, some special ground heat exchangers have been developed exploiting a smaller area at the same volume. These collectors are best suited for heat pump systems for heating and cooling, where natural temperature recharge of the ground is not vital.

The main thermal recharge for all horizontal systems is provided mainly by the solar radiation to the earth's surface. It is important not to cover the surface above the ground heat collector, if it has to be located, for example, under a building. Ground can also act as a rechargeable heat store, during summer, the heat from building will be removed and dumped in the ground to cool the buildings and in winter, this stored heat in the ground will be used to warm the building.

The horizontal-loop systems can be buried beneath lawns, landscaping, and parking lots. Horizontal systems tend to be more popular where there is ample land area. Care must be taken to ensure that each pipe run is not long enough to cause the pressure drop, as this would increase the pumping costs. Furthermore, all the pipe runs should be of the same length to ensure same pressure drop, flow and heat transfer conditions. Circa 35 – 60m length is required for each kW of heat, with extraction rate of 15 – 30 W m^{-1} (Florides and Kalogirou, 2007).

The horizontal loops can be laid either in series or in parallel as shown in Figure 2.22. The dense pattern of pipe maximises the heat transfer for the space available. A minimum distance of 3 meters is required to prevent thermal interference.



.

Figure 2.22: Horizontal loops reproduced from (Earth river geothermal Ltd, 2016).

Advantages: Trenching costs are much lower than well-drilling costs and relatively simpler installation process.

Disadvantages: a large ground surface area is needed, since the depth is shallow, the ground temperature is subject to seasonal variations; the thermal properties of soil vary with season, rainfall, and burial depth, longer pipe lengths are required than for vertical wells, the antifreeze solution's viscosity increases pumping power, decreases the heat transfer rate, and thus impact the overall efficiency.

2.8.1.2.2 Spiral loops

When there is a shortage of area available for trenching, a multiple pipe horizontal-loop configuration in the spiral loop, commonly referred to as the ‘slinky’ is used. The spiral loop consists of pipe laid in circular loops in trenches in the horizontal configuration. Another type of the spiral-loop system involves laying the loops upright in narrow vertical trenches. The spiral-loop configuration generally requires more piping, typically 500 to 1000 feet per cooling ton (43.3 to 86.6 m kW^{-1}) (Omer, 2008). In the horizontal spiral-loop layout, the trenches are normally spaced 0.9 to 1.8 m wide; multiple trenches are normally spaced about 3.7 m apart (Omer, 2008). For the vertical spiral-loop layout, the trenches are normally 15.2 cm wide and the pipe loops stand vertically in the narrow trenches (Omer, 2008). In cases where trenching is a large component of the overall installation costs, spiral-loop systems are a means of reducing the installation cost.

Advantages: Requires less ground area and less trenching than normal horizontal loop designs, installation costs slightly less than normal horizontal loop designs.

Disadvantages: More total pipe length required than normal horizontal design, relatively large ground area is required, ground temperature subject to seasonal fluctuations, larger pumping energy requirements than normal horizontal loops described earlier, backfilling the trench can be challenging with certain soil types and the pipe system could be damaged during backfill process.

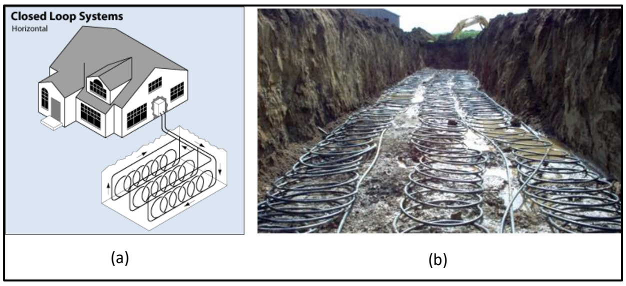


Figure 2.23: Slinky (a) Slinky loop configuration (US Department of Energy, 2016b), (b) 3-ton slinky at a site (Mark Johnson, 2006).

2.8.1.2.3 Vertical loops

If sufficient ground area is not available to lay the horizontal loops, then the loops are laid vertically by drilling bore holes to depths that typically range from 20 to 90 m deep (Omer, 2012). The closed-loop pipes are inserted later into the borehole. Measurements have shown that the temperature below a certain depth ("neutral zone", at 15-20 m depth) remains constant over the year (Jo, et al., 2001). Polyethylene or Polypropylene materials generally used for loops and the remaining annular space between the loop and borehole is backfilled) with grouting material. If more than one borehole is required, then care must be taken to ensure there is equal flow in all the channels. As a thumb rule circa 0.75 kW of heat requires 10 m length of borehole (Banks, 2012). According to Omer (2008), typical piping requirements range from 66 to 200 m per system cooling ton (17.4 to 52.2 m kW^{-1}), depending on soil and temperature conditions. Multiple wells are typically required with well spacing not less than 4.6 m in the northern climates and not less than 6.1 m in southern climates to achieve the total heat transfer requirements. A 300-500 ton capacity system can be installed on one acre of land, depending on soil conditions and ground temperature (Omer, 2008).

The two most commonly used configurations of the vertical loops are (Omer, 2012):

U-pipes: it consists of a pair of straight pipes that are connected by 180^0 turn at the bottom. One, two or even three of such U-pipes are usually installed in one hole. The main benefits of the U- pipe are the low cost of the pipe material, with the double U pipes being the most commonly used in borehole.

Coaxial (concentric) pipes: in this configuration fluid flow and return takes place in a coaxial pipe. The design can be very simple way with two straight pipes of different diameter, or can be in complex configurations.

2.8.1.2.3.1 Advantages of vertical loops are:

- Requires lesser pipe material than most horizontal loop designs.
- Requires the less pumping energy than closed-loop systems.
- Occupies lesser footprint.

2.8.1.2.3.2 Disadvantages of vertical loops are:

- Requires drilling equipment.
- Initial costs are higher due to drilling.
- Potential problems in getting planning permissions from the council and environment agencies.

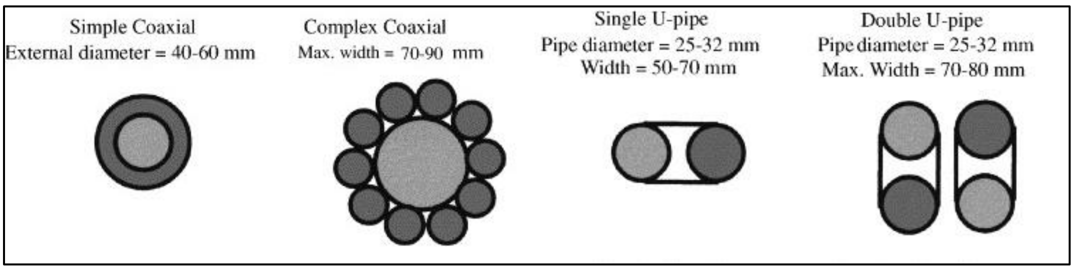


Figure2.24: Vertical loop configurations (Florides and Kalogirou, 2007).

2.8.1.2.4 Submerged loops

If a pond or lake is available near to a building with sufficient heat demand, then closed loop piping system can be submerged in the pond. Ponds also improve facility aesthetics and few organizations maintain a pond on their facility. This type of system needs sufficient surface area and depth to respond to the heating or cooling requirements under local weather conditions. Omer (2008) recommends the following criteria for the installation, a piping length of 300 feet per ton (26 m kW^{-1}) and 3000 ft^2 of pond surface area per ton (79.2 m^2 kW^{-1}) with a recommended minimum one-half acre total surface area. The concrete anchors hold the pipe securely and prevent the movements. The pipe should be at least 9 to 10 inches above the pond floor to allow good convective heat transfer around the pipe surface. In addition, the pipe loop must be at least 6 to 8 ft. below the pond surface, so that even during dry and drought conditions there is sufficient thermal mass available for heat transfer. A 5.4 MW cooling and 5 MW heating capacity heat pump has been installed at Kingsmill hospital in Mansfield, UK, the heating loops have been placed in the nearby Kingsmill Lake, the system has been in operation since 2008 (GI Energy, 2016). A feasibility study on using the water from a water treatment reservoir in Korea has been described by Oh, Cho and Yun in (2014). A study on the heat pump performance and potential benefits in using sea water as heat source has been described by Baik, et al. in (2014). The immense potential the waters in reservoir have as a heat source for the heat pump applications has been described in detail by Kindaichi, et al. in (2015).

Advantages: Pipe length required can be less and capital cost can be less expensive compared to other closed-loop designs.

Disadvantages: Requires a large body of water, other uses of lake like boating or swimming might be restricted and flora and fauna of the pond might be affected if the temperature of the pond is altered (Earth river geothermal Ltd, 2016).

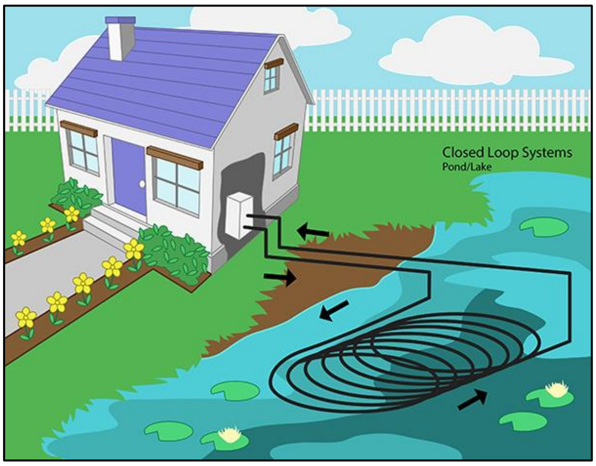


Figure 2.25: Pond loop (wellowner.org, 2016).

2.8.1.3 Direct and Indirect Expansion

Based on the operation of the closed loop GSHP, it has been classified as direct expansion (DX) and indirect expansion system.

In direct expansion system, the working medium of the heat pump (refrigerant) is circulated directly through the closed loop pipes, here the ground acts as an evaporator for the heat pump. The advantage of this system is the increase in thermal contact area and better heat transfer, no circulation pump, omission of the heat exchanger between the ground coil and the refrigerant and thus can achieve a better system efficiency. Direct expansion (DX) requires a good knowledge of the refrigeration cycle, and is restricted to smaller units. Mostly copper tubes are used for the piping. If a toxic refrigerant like HCFC 22 is used and it leaks, it could cause environmental issues.

Indirect system uses a circulation fluid that is a mixture of water and antifreeze to transfer heat from the ground to the heat pump. The circulating fluid can be mixed with salts or a glycol solution. Care must be taken when choosing the brine, as the pumping costs would increase if the viscosity of the brine is high.

2.9 Summary

This chapter has presented the details of the literature survey undertaken. A description of the coal mining operations including the techniques and subsequent mine water rebound due the closure of the mines has been presented. The key parameters in estimating the thermal energy content of mine water are identified. A detailed description of the heat pump including the principle behind its operation, types of heat pumps and various configurations of operating a heat pump are also presented. Benefits of using mine water in a heat pump have also been described.

3 Methodology

3.1 Introduction

From the previous chapter, it was evident that the need to reduce carbon emissions and mitigate the climate change phenomenon is driving people to look at alternative sources for energy and heat pump technology is seen as an alternative method to heat the buildings instead of the conventional gas boilers and electric heaters. Vast volumes of mine water in the abandoned coal mines that are posing a threat to the environment and possess low enthalpy energy have a great potential to be used for space heating in conjunction with GSHP. This research work investigates the feasibility of using mine water for space heating in conjunction with a GSHP and take this novel concept from conceptual phase to commercial deployment ready phase.

The demand for the conventional fuels coal, gas, oil etc. is increasing rapidly due to a huge growth in the population of the world. Conventional fuels being a finite resource, its availability is decreasing, leading to a huge increase in their prices. Additionally, conventional fuels are contributing to an increase in carbon levels in the atmosphere causing the climate change. Hence, the need to find alternate fuel sources has increased. With UK having signed pacts to reduce carbon emissions significantly from the current levels, it has to find alternative low carbon energy sources to meet its carbon emissions commitments. Meeting the heating and hot water needs using a GSHP on large scale can be one such alternate method.

The closure of coal mines has led to a rise in mine water levels and is posing a threat to the environment. To prevent this, at many places large volumes of mine water are being pumped to surface and are being treated before discharging to a stream, putting a considerable economic burden on the local councils. This mine water possesses low enthalpy energy and if a part of this energy can recovered, it would alleviate some of the financial burden faced by the local authorities. Mine water contains many dissolved salts and ions and can pose operations and maintenance problems. This apprehension is preventing people from looking at it as an alternate energy source. Through this research work, it proposes to show that by careful design, mine water can be useful as an energy resource for heating and the major issues related to maintenance and operations of the plant can be eliminated.

This chapter describes the methodology used for addressing the above requirements along with the reasoning behind its usage.

3.2 Aims of the research

The main aim of this research is, to evaluate the feasibility of using the water from the flooded and abandoned coal mines for space heating using a GSHP in open loop configuration, to take a conceptual idea to a commercial deployment stage and to stimulate the uptake of this technology by highlighting the economic and environmental benefits of implementing the scheme through this work.

To meet this aim; the subsidiary objectives are to:

1. By literature survey, review the theoretical aspects of coal mining methods, mine water and flooding of the mines. Identify the key parameters that have an impact on the energy content of mine water and devise a method to estimate the potential thermal energy that can be harnessed from those details.
2. By literature survey, review all the aspects about the heat pumps including the theory behind the working of the heat pumps, heat pump types, heat pump components, the various modes of operations and different configuration setups.
3. Identify the key parameters required for sizing the heat pump, borehole pump and components like heat exchanger and buffer tank. Develop a generic mine water based GSHP system design based on the peak heat demand requirement.
4. Develop a design and commercial evaluation tool to design a mine water based GSHP system covering technical, economic and environmental aspects.
5. Conduct feasibility case studies for potential sites (Markham, Caphouse and Chatterley Whitfield), covering all aspects including technical, economic and environmental factors.
6. Design and build test rig pilot plants to conduct field trials at two sites (Markham and Caphouse) with different infrastructure and water qualities.

7. Analyse the data from these field trials, including the maintenance aspects along with the performance.
8. Measure the potential benefits of using mine water based GSHP in comparison with conventional heating systems and conclude the findings with suggestions.

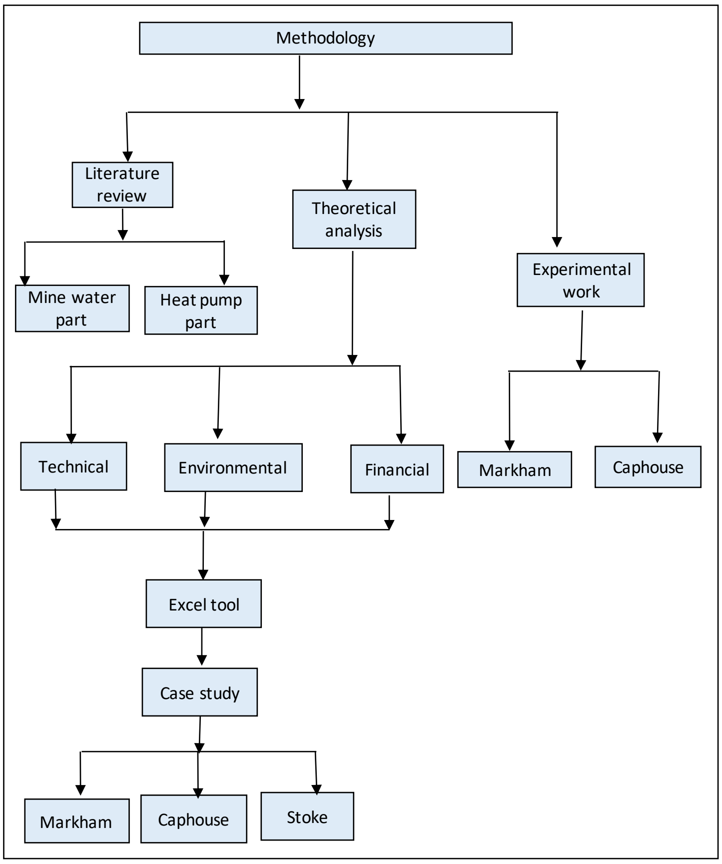


Figure 3.1: The schematic layout of the research methodology.

Figure 3.1 shows the schematic diagram of the research methodology used for this research work. The research methodology outlines a three stage process used to investigate the feasibility of using mine water to heat the buildings using a GSHP. In the first stage, a literature review is undertaken to understand the coal mining operations, mine water recovery; post mine closures, heat pump operation, various types of heat pumps and economic and environmental benefits of using a heat pump. In the second stage, a theoretical analysis including all the technical, financial and environmental aspects are used in the design of a mine water based GSHP system. An MS Excel based tool is developed based on the theoretical analysis. Three theoretical case studies are carried out to check the feasibility of implementing a mine water based GSHP. Two pilot plants are built for the field studies and experimental work is carried out to check the actual field performance of the GSHP plant with mine water, with the emphasis on the operations and maintenance. The size of the pilot plants built is smaller than the size considered for the case studies. This is because of the limitation on the amount of funding available to build the plants and the high costs required for the full scale plants are not justifiable just for a testing. Depending on the success of the operations of the pilot plants, plans are there to expand it to a full scale system. Further details on the three processes used for the methodology are mentioned below.

3.3 Literature survey

The literature survey part is divided into two parts, namely mine water part and heat pump part. In mine water part, all aspects related to mine water, starting from underground coal mining techniques, dewatering during the mining operations, flooding of the coal workings following the closure and abandonment of mines and the subsequent rise of mine water levels, and the threat posed to the environment by those rising mine water are covered.

In the second part all the aspects of the heat pump regarding the theory behind it including, the refrigeration cycle, the working of a heat pump, types of heat pumps, operating modes, configurations, and different ancillary parts needed are covered. The economic and environment benefits of the heat pump are also included in this part.

3.4 Theoretical Case studies

From literature survey, a theoretical analysis is undertaken to design a mine water based heating system. This includes identifying the key parameters that should be considered for designing an open loop based GSHP (Ground Source Heat Pump). Calculating the potential energy that can be harnessed when the details of mine water pumping sites are known or when the maximum heat demand requirements are known.

The theoretical analysis also includes the technical, financial and environmental aspects as well. The financial feasibility is measured through IRR and NPA methods. The environmental aspects included, calculating savings in carbon emissions that can be obtained when compared with the traditional heating system. An MS Excel based generic tool is developed to design and commercially evaluate a mine water based heating system. The tool is described in detail in the chapter 4. Three feasibility case studies are conducted for sites at Markham, Caphouse and Chatterley Whitfield, Stoke, see, Figure 3.2. Each of these sites has different mine water abstraction conditions. At Markham an existing mine water shaft is used, here abstraction of the warm water and the discharge of the spent water occurs in the same shaft. At Caphouse mine water is already being pumped out for water treatment purpose and energy from the raw water is extracted before the treatment process. At Chatterley Whitfield, Stoke, similar to Markham, has an abandoned mineshaft where mine water has recovered to a level just below the surface. The details of all the case studies are presented in chapter 5.

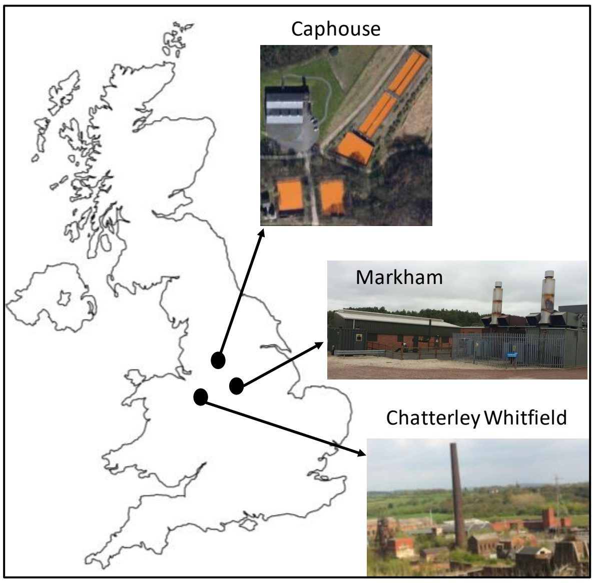


Figure 3.2: The location of the case studies sites in UK.

3.4.1.1 Site 1 Chatterley Whitfield, Stoke.

Chatterley Whitfield is a region under the Stoke city council. Chatterley Whitfield colliery site after its abandonment has been converted into an enterprise centre housing many businesses. Abandoned Hasketh mineshaft is open and lies within the enterprise complex, see Figure 3.3. The water level in the shaft is just 18 m below ground level. A feasibility case study is conducted for installing an open loop mine water based GSHP system to use mine water to heat the enterprise centre buildings. The design considered using a single shaft to pump the warm water and discharge it back to the same shaft, but at different level. No pilot plant is constructed at this site.

Figure 3.3: Hasketh Shaft.

3.4.1.2 Site 2: Caphouse colliery, UK

The Caphouse colliery complex, which closed in the year 1985, was converted into a museum after a couple of years, where the underground galleries are opened to public. In order to keep the underground galleries, dry and safe for the public, nearly 30 litres per second of water is pumped from the pit and discharged into river Calder. Mine water is treated to remove the ochre before discharging. The case study is conducted to use the energy from the water and heat a part of museum building. The water here is prone to ochre clogging and hence a smaller pilot plant using a small volume of the pumped water is built to test the performance. Prophylactic shell and tube heat exchangers are used to minimise the ochre clogging issues and ensure continuous operations. Since the water is already being pumped there are no additional pumping costs.

Figure 3.4: Google map of Caphouse mine water treatment facility.

3.4.1.3 Site 3: Alkane Energy, Markham, UK

Alkane Energy site at Markham was the site of former Markham Colliery. Alkane Energy have their control centre and maintenance depot at this site and need heating 24×7. This site has an open but flooded mine shaft where the water is deep but raising. A case study is conducted by considering a peak thermal demand for the current buildings and also for the additionally planned building in the future. A pilot plant is constructed to heat only the current Alkane premises. The water is pumped and discharged from the same shaft but at different heights.

Figure 3.5: Alkane Energy, Markham.

3.5 Experimental Work

Chapters 6 and 7 present the details and the performance of the pilot plants that are constructed at the two sites, namely at Markham and at Caphouse. The experimental work is carried to see the working of a theoretical concept in action. The size of the pilot plant built is smaller than the size used for the feasibility case studies, this is because of high costs required for a full-scale plant. This pilot plant is mainly to see the actual performance of using the mine water in the field. All the findings of the experimental work are presented later in chapter 7.

3.6 Expected Contribution to Knowledge

- Evaluate the potential of mine water as an energy source for heating along with GSHP.
- Evaluate the potential financial and environmental benefits of using an open loop configuration of GSHP when mine water is used as source of energy.
- Development of a generic design tool to design a mine water based open loop GSHP.
- Bring a theoretical concept to a commercial deployment level by building the pilot plants and test the operational feasibility of using mine water in open loop configuration of GSHP for heating.
- Provide confidence in the technology by demonstrating its performance in the field and help in its uptake.

3.7 Summary

This chapter has presented the research methodology used for investigating the concept of using mine water for space heating. The research work aims to use mine water that is an environmental liability into an economic resource by using it for space heating. A three stage process is used to bring a theoretical concept into a commercial deployment level. In the first stage, a literature review is carried out. In the second stage, theoretical analysis is carried out to bring the concept to a workable design stage and it involves conducting the case studies for three sites. In the third stage, experimental work is carried out by building the pilot plants at two sites to test the concept in action.

4 Design of mine water based heating system

Following the literature survey, the main parameters required in the design of a mine water based heating system are identified and a tool is developed in MS Excel to conduct the theoretical case studies. This chapter mentions the details of all the process that has been used in the design.

A schematic of the design tool developed is given in Figure 4.1. The system is designed based on the peak thermal power output required; the customer who needs the heat gives this value. Additionally, heating demands of the building can also be calculated based on the building material and the geometry. The heating requirement of the building is not calculated here and is beyond the scope of this work. However, there are many proprietary and free tools available to calculate the heating requirements of a building based on the geometry and the building material. Once the customer gives their peak thermal power output requirement, the step by step design process is used. First, the size of the heat pump is selected, then, the borehole pump or mine pump is selected and later heat pump accessories are selected. Under the financial section the savings and other incentives that can be obtained by using the GSHP are calculated. Then the environmental aspects on the amount of carbon emissions that can be saved in comparison with a traditional GSHP is calculated.

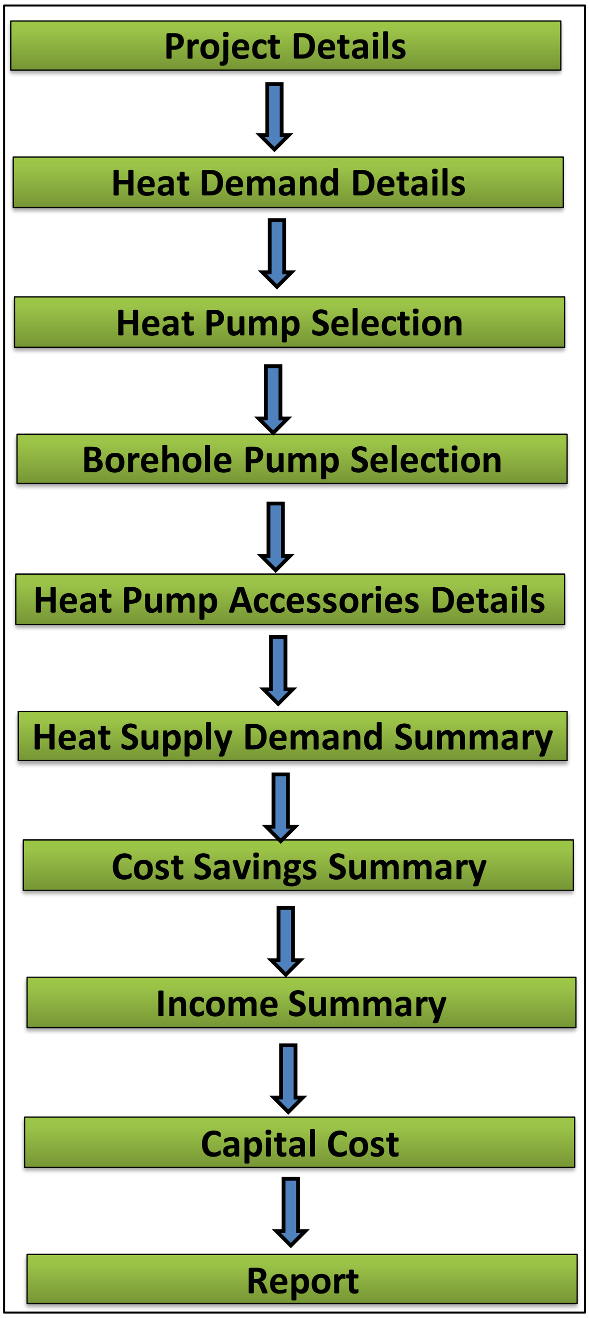


Figure 4.1: Schematic of the Design Tool.

4.1 Technical

4.1.1 Peak and annual heat demand

The total annual heating demand of a building is calculated based on their peak thermal power output, number of hours the heating required and the total number of heating days in a year. Figure 4.2 shows the schematic of how the annual heat demand is calculated, see Equation 13. The customer gives details of the peak thermal power, number of heating days in a year and the demand profile of the building in a day.

Most of the buildings do not need to be heated throughout the year, but only during the winter period, early spring and late autumn period. Usage profile of the building is also an important parameter that needs to be considered while calculating the annual heat loads, some offices operate from morning till evening while some others operate throughout the day.

Annual Energy demand in kWh = No. of heating days in year × No. of hours of heating needed in a day × peak thermal power of the heat pump in kW (13)

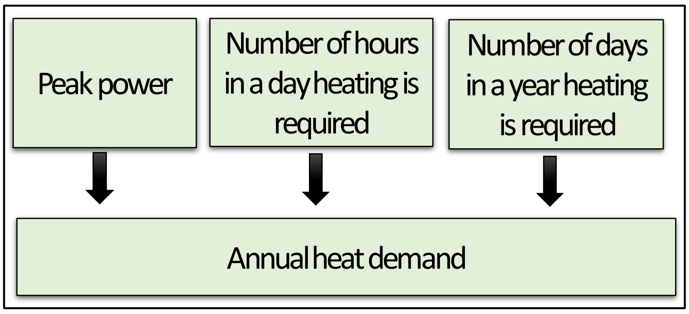


Figure 4.2: Annual heating demand.

4.1.2 Mine water specifications

There are many abandoned mineshafts and boreholes available that can be used to extract mine water, however, for a larger load, it is recommended to conduct a pump tests to ascertain the maximum extraction rates and water properties from those shafts and boreholes. The standard '(BS ISO 14686:2003, 2003)' mentions the standard procedure on how to conduct the pump tests.

For this research work, water properties of the sites where field trials were conducted were well known in advance, hence no pump tests were conducted. The two sites chosen for the field trials are, at Caphouse, an existing dewatering site where the pumping rates are known and at Markham, a very small flow rate of 2-3 litres per second is pumped from an existing mine shaft (holding huge quantities of water, with fresh inflows into the shaft, the water level is rising at a rate of 2 meters per month at Markham).

Based on the temperature of mine water, the flow and return temperatures (ΔT of mine water) are set. It is usually between 2 to 5 ^{0}C. The temperature of mine water in UK varies between 13 to 14 ^{0}C (Banks, et al., 2004) at a depth of 100 m and it increases as we go deeper. In order to protect the clean water bodies from the rising mine water levels, dewatering is actively being carried out even when the mines have been abandoned. The Coal Authority in UK is actively pumping a combined volume of 3000 litres per second of water from 64 sites throughout UK (Bailey, et al., 2016), the temperature of this water is circa 15 ^{0}C (Younger, 2014). The existing dewatering sites are ideal as all the water properties and flow rates are well known (Caphouse, chosen for the field trails for this research is one such site).

4.1.3 Heat Pump sizing

The COP of the heat pump is chosen based on the manufacturer’s datasheet and advice, the COP of most of the commercial heat pump varies between 3 to 6 (Bazargan Sabet, Demollin and Van Bergermeer, 2008). The amount of thermal power that is required from mine water ‘P_{mw}’ is calculated based expected value of the COP, peak thermal power and electricity consumption of the heat pump. See Equation 14, 15 and 16.

$$\frac{P_{hp}}{COP_{hp}} = HP_{electricity} \qquad (14)$$

Where 'P_{hp}' is peak thermal power of the heat pump in kW.

'COP_{hp}' is the coefficient of performance of the heat pump, obtained from the manufacturer's datasheet or from their technical team member.

'$HP_{electricity}$' is the peak electrical power required to operate the heat pump in kW.

$$P_{mw} = P_{hp} - HP_{electricity} \quad (15)$$

$$P_{mw} = \rho_w . C_p . \Delta T . q \quad (16)$$

'P_{mw}' is the thermal power harnessed from mine water in kW.

'C_p' the specific heat of the water and is 4.18 kJ $kg^{-1} K^{-1}$.

'ρ_w' is the density of water 1000 1000 kg m^{-3}.

'Δ T' is differential temperature in K.

'q' is volumetric flow rate of water in $m^3 s^{-1}$.

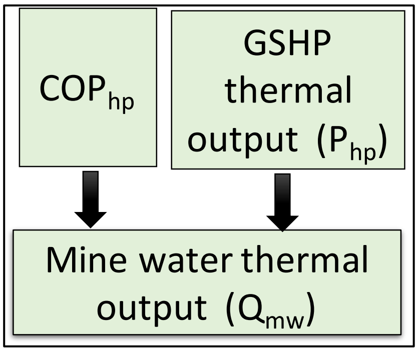


Figure 4.3: Mine water energy requirements.

The Figure 4.3 shows the schematic of the thermal power required to be harnessed from mine water. The amount of thermal power that is required to be harnessed from mine water depends on the efficiency (COP) and peak thermal power output of the GSHP, see Equation 15. Greater the efficiency lesser will be the electrical power required for the heat pump.

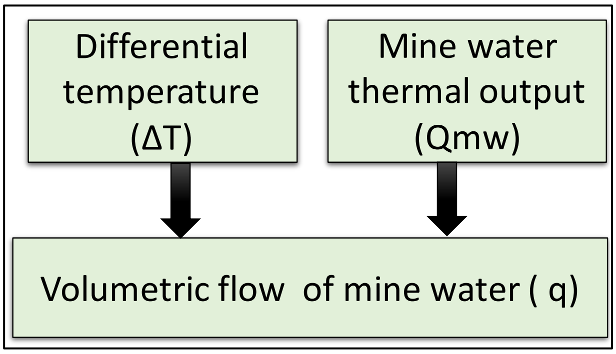


Figure 4.4: Mine water flow requirements.

Once mine water thermal power required is known and the differential temperature is fixed, the flow rate required is calculated. See Equation 16. Figure 4.4 describes the schematic for the flow rate of calculation.

4.1.4 Borehole pump sizing

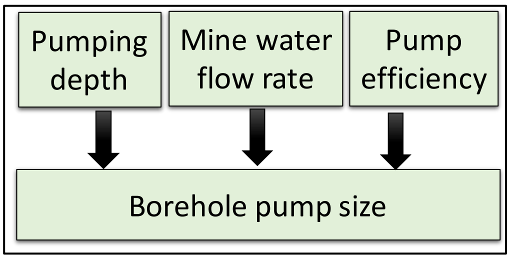


Figure 4.5: Borehole pump size calculation schematic.

The borehole pump size required depends on the depth from which the water has to be pumped and the flow rate of mine water required. See Equation 17. Greater the pumping depth, greater will be the electrical energy required. This has a negative impact on the overall efficiency of the system. If an existing dewatering site is selected, then there is no need to consider this step. The overall efficiency of the whole system increases as no additional power is needed to operate the borehole pump and the operating cost decreases; it is almost equal to that of the heat pump (Athresh, Al-Habaibeh and Parker, 2016). The borehole pump efficiency of 5 (kWh/Ml/m) is considered to be suitable and is taken as a standard at the Coal Authority in UK (Athresh, 2015).

The Coal Authority run and operate various mine water treatment and dewatering schemes in UK (Coal Authority UK, 2016).

$$MP_{electricity} = \eta_{borehole} \times \text{pumping depth} \times \text{flow volume} \qquad (17)$$

Where, $\eta_{borehole}$ is the efficiency of the borehole pump, it measured as kWh per mega litre per meter lift, 5 is taken as a standard, pumping depth in meters and flow volume in mega litres.

4.1.5 Buffer Tank sizing

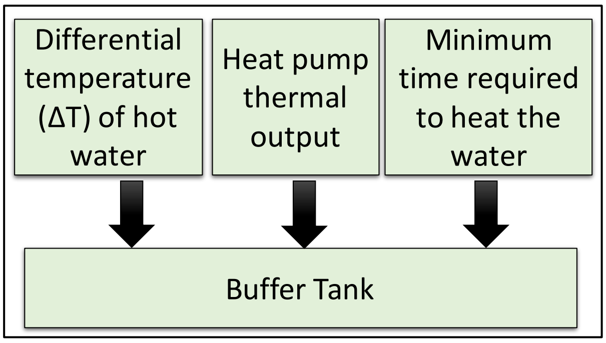


Figure 4.6: Buffer tank calculation schematic.

In order to improve the efficiency of the compressor of the heat pump and reduce cycling of the compressor, a buffer tank is required to store the hot water. Figure 4.6 shows a schematic of the variables needed to calculate the size of the buffer tank. Equation 18 below gives the volume of buffer tank needed to store the water (Viessmann UK, 2012). It is based on the peak thermal power output of the heat pump P_{hp} in kW, minimum time required to raise the temperature of the entire volume of water in the buffer tank, it normally taken as 600 seconds (10 minutes) (Viessmann UK, 2012). ΔT is the flow and return temperature of the hot water from the building, 10 ^{0}C is normally considered. 'm' is the mass in kg.

$$t_{buffer} = \frac{m.Cp.\Delta T}{P_{hp}} \qquad (18)$$

4.1.6 Brine flow rate

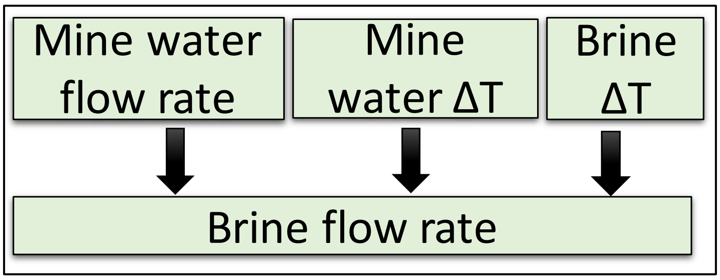


Figure 4.7: Brine flow rate calculation schematic.

In order to minimise any potential problems due to mine water quality, a heat exchanger is used to isolate mine water circuit from the heat pump circuit. The brine flow rate depends upon the flow and return temperatures of mine water and mine water flow rate. It is calculated using the Equation 19.

$$q_{brine} = \frac{Q_{mw}}{\Delta T_{brine} \times C_{p\ brine} \times \rho_{brine}} \tag{19}$$

'Q_{mw}' is the power harnessed from mine water in kW.

'$C_{p\ brine}$' is the specific heat of the brine, it is brine dependent, here the brine (Solaris DTX) has a specific heat of 3.62 kJ.kg^{-1}. K^{-1}.

'ΔT_{brine}' is the density of water 1060 kg.m^{-3}.

'ΔT_{brine}' is differential temperature in K.

'q_{brine}' is volumetric flow rate of water in m^{3}s^{-1}.

4.2 Economic

Whether a project goes ahead or not mainly depends if it is financially viable for the investors in the project. Many of the renewable energy projects get a green signal to go ahead because of the expected benefits in form of receiving financial incentives or savings due to the reduction in energy costs. Many big corporations and local councils look for environmental impacts and reduction in carbon emissions as one of the criteria and go ahead with the project even if it is financially not attractive, as it benefits the organisations in achieving their overarching goals. This section discusses the process used for analysing the financial aspect of installing a mine water based heating system.

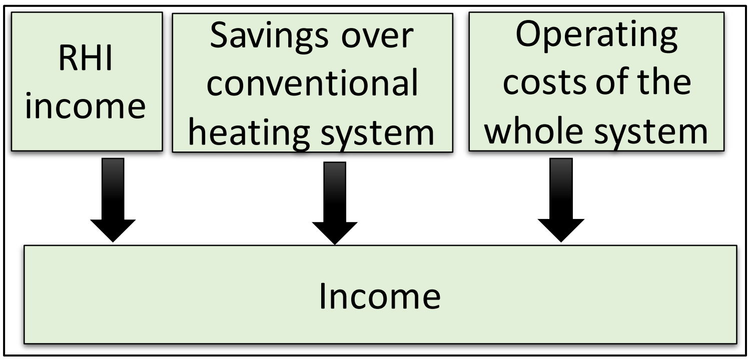


Figure 4.8: Income schematic.

The amount of income that can be generated depends on the RHI income, savings in heating costs compared to a traditional heating system and the operating costs involved due to the electricity consumption of the heat pump and the borehole pump.

4.2.1 Capital Costs

Of the two sites selected for the research study, Markham has an existing open shaft and the water is extracted and then the spent water is returned back to same shaft, at Caphouse, the water is already being pumped and discharged to a stream after removing all the effluents from it. There are 64 sites in UK, pumping circa 3 cubic meters of water per second (Bailey, et al., 2016; David Banks, 2013). It these sort of sites that this study aims to target, as these sites do not require any drilling of boreholes or cumbersome environmental agency and council applications. The heat emitters on the building side for the two study sites are compatible for low and medium temperature water flow. If a mine water based heating system needs to be installed in a new development or retrofitting in an existing building, the heating system has to be custom designed and has not been discussed here.

The cost of the equipment is based on the actual cost incurred to purchase the equipment. The list of all the equipment is given in the Table 4.1. The costs vary based on size and capacity and the equipment cost for this study has been calculated using the actual quotes from the suppliers.

Table 4.1: GSHP system equipment list

Component	Cost
Plant room	Actual cost incurred
Borehole pump	Actual cost incurred
Filter	Actual cost incurred
Heat exchanger	Actual cost incurred
Heat Pump	Actual cost incurred
buffer tank	Actual cost incurred
heat meters × 2	Actual cost incurred
Control system	Actual cost incurred
Plumbing connections	Actual cost incurred
Trenching	Actual cost incurred
Electrical connections	Actual cost incurred
Design and project management costs	Based on the quotation from the contractors

4.2.2 Operating costs

Heat pump requires electricity to run the compressor. If a borehole pump is used then, it consumes additional electricity. If distance of the heat pump system is far from the heat recipient building or if mine water borehole is not close to the heat pump system, then circulating pumps will be needed to pump the water around the building and the heat pump system. These pumps consume additional electricity and increase the operating costs and decrease the overall COP of the system. See Equation 22.

$$COP_{hp} = \frac{\text{Thermal Energy produced by the heat pump}}{\text{Electrical Energy consumed by the heat pump}} \quad (20)$$

$$COP_{hp} = \frac{P_{hp}}{HP_{electricity}} \quad (21)$$

$$COP_{system} = \frac{P_{hp}}{HP_{electricity} + MP_{electricity} + CP_{electricity}} \quad (22)$$

Where, $HP_{electricity}$ is the electricity consumed by the heat pump in kWh.

$MP_{electricity}$ is the electricity consumed by the borehole pump in kWh.

$CP_{electricity}$ is the electricity consumed by the circulation pump, this is negligible if the heat recipient building, heat pump system and mine water bore hole are close to one another.

At Markham site, the recipient building, heat pump system and mine water borehole were all in close proximity, hence power consumed by the circulation pump has been neglected. At Caphouse site, small amount of mine water has been tapped from main mine water discharge line. Hence, there is no power consumption from either the borehole pump or the circulation pump.

If mine water which is already being pumped is used, then,

$$COP\ hp \approx COP\ system \quad (23)$$

No operator cost has been considered, as these systems are programmed to work automatically when the demand for heat arises, just like the conventional electric heaters and gas boilers.

4.2.3 Maintenance cost

Mine waters can be saline and the salinity is slightly less than seawater. Corrosion can be an important factor that can influence the working of the system, as salinity causes corrosion. Most of the pipe materials are made of plastic and hence are not affected by corrosion. The heat exchangers and the filter are made of marine grade material and hence they are also not affected by corrosion. Two prophylactic heat exchangers (one on standby) are employed to prevent mine water from entering into the heat pump directly, instead an intermediate brine solution is used to transfer the heat from mine water to the refrigerant of the heat pump. If any corrosion or clogging were to occur, it would be restricted only to the heat exchanger (heat exchanger are cheaper and easier to replace), this minimises the risk of any problem to the heat pump due to mine water. The duplex filter has two filter baskets and the water flows through only one of the basket, if the filter basket gets clogged due to any particles, the flow can be switched over to the other basket just by turning the knob, the unclean basket can be removed and cleaned. The whole process is very quick and takes only 15 minutes. The duplex filter filters out most of the particles from the water before it enters the heat exchanger. The GSHP's are designed to operate for 25 years without any problem.

At Markham, the quality of mine water was tested and was found to be very good and the quality was comparable to that of normal ground water. Hence, no problems of either corrosion or clogging is anticipated. The water is kept completely concealed and prevented from coming in contact with the air at any point of time during the pumping process, this is to prevent the formation of iron ochre. Iron ochre is formed when the dissolved iron in the water is exposed to the atmospheric oxygen (Banks, Pumar and Watson, 2009). At Caphouse, mine water is partially oxygenated in the shaft and hence ochre is formed and is treated before it is discharged into the stream (Kruse, 2007; Burnside, Banks and Boyce, 2016). It is therefore anticipated that ochre will pose problems. However, the presence of duplex filter and standby prophylactic heat exchanger should ensure in continuous operation of the heating system, without any major problems.

4.2.4 Savings

As mentioned earlier in the literature review chapter, when compared with the conventional heating sources, the heat pump produces 3 to 6 times (based on the COP of 3 to 6) more thermal energy as output than electricity it consumes as input. At Markham, Alkane Energy office was using electric heater to heat the building. Considering a best efficiency of 100 % for the electric heater (US Department of Energy, 2016a), the heat pump will perform much better than this.

At the Caphouse, a gas boiler with an efficiency of 85% was being used to heat the Inman shaft building. Considering that there is no pumping is involved, the overall savings will be much higher.

4.2.5 RHI income

The UK government, in order to its meets target to ensure that 12 % of its heating energy comes renewable energy sources by 2020. (Department of Energy and Climate Change (DECC), 2011) introduced the Renewable Heat Incentive (RHI) scheme in July 2011 (Robert Irving, 2013). RHI is a system of providing financial incentive to people for sourcing their heat energy needs from technologies that are deemed to be renewable heating systems and heat produced from ground source heat pumps is eligible to receive this incentive.

This scheme is open both for domestic and commercial sectors. Subsidy is paid for every kilowatt hour of heat produced by the GSHP system. OFGEM has laid out the minimum performance criteria that needs to be met by the GSHP in order to receive the payments. The main criteria for the GSHP that need to be met are (OFGEM, 2015):

- Have a minimum COP value of 2.9.
- Have a minimum SPF of 2.5.
- The primary source of heat must be from natural sources like earth or water and must not be anthropogenic like exhaust heat.
- GSHP must be sized according to the design conditions of heat requirement.
- For a reversible system, RHI is paid only for the heating operations and not for cooling operations.
- The heat generated must be properly measured using meters approved by OFGEM (OFGEM, 2015).
- If there is a provision for electric, gas or oil based backup heating, then heat generated from them must be measured.
- Only the owner of the installation can claim the RHI.
- If the installation size is less than 45 kW thermal load then, the plant has to be installed by an MCS accredited installer.

RHI payment is paid for a period of 20 years from the date of commissioning the system, with the payment being made on a quarterly basis. The RHI tariff for the GSHP is based on two tiers. The first tier is applicable to the amount of heat generated by GSHP if it was running at capacity for 15 % of the year, any heat generated above this comes under the second tier of payment. The tariffs are index linked and change periodically due to inflation.

Table 4.2: RHI Tariffs for non-domestic GSHP

Non Domestic RHI Tariffs(Ground Source Heat Pump Association, 2016c), as on 20/8/16	
Tier 1	£0.0895/kWh
Tier 2	£0.0267/kWh

The domestic installations receive the RHI payments for a period of 7 years only, but they receive a single tier higher tariff of £0.1933 for every kilowatt hour of heat generated by GSHP (Ground Source Heat Pump Association, 2016b). This research work does not consider the domestic installation for the study, as very few residential houses are built near mine water dewatering stations or near to collieries (as there might be subsidence problems) and the amount of heat required by the domestic houses is very small. There is always a risk of government withdrawing this scheme or changing the tariffs. Hence, this risk has to be factored in.

4.2.6 Financial model

The methodology used in building the financial model to calculate the return on investment has been described here. MS Excel was used to develop the financial model. Each of mine water based heating system configurations used for the case studies are examined from an economical point of view as well. Based on the heat demand requirement and the estimated value of COP (obtained from the heat pump manufacturer), the electricity required to operate the heat pump and the borehole pump (if necessary) is calculated. Based on the annual heat profile of the customer site, the annual energy demand was calculated. Based on this operating cost and the annual energy demand, the cost to produce one kilo watt hour of heat from the heat pump was deduced. The savings in energy cost and energy consumption is obtained in comparison to the conventional heating system. Additionally, the incentives that can be received from RHI scheme are included in the annual revenue stream. Annual profit was deduced after subtracting the annual operating cost from the annual income. The equipment cost for most of the components required for each of case study site was obtained from component manufacturers.

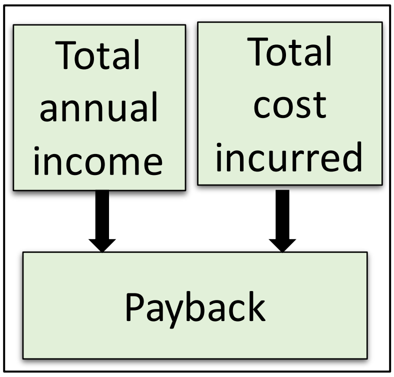


Figure 4.9: Payback

Before making any decision in any investment, the main issue on the investors mind is the payback period. Lesser the payback period more attractive the project becomes for the investor. Figure 4.9 shows the schematic of the variables required for calculating the payback period.

In order to streamline the cash flow analysis, the following assumptions were made:

- The installation cost is paid completely at the beginning of the project and no loan is taken to fund it.

- The project life of 20 years is considered, (RHI contract is for 20 years and payments are paid for the entire duration of 20 years).
- The savings in utility bill when replacing the gas heating and electrical heating are considered in the cash flow. According to Energy Saving Trust (The Energy Saving Trust, 2016), the average electricity price in UK was £0.1386 and average gas price in UK was £0.0434 for the year 2015-2016. When the actual price at which the customer purchased their electricity was available, that value was used.
- The inflation is taken into consideration. It is calculated as an average of 3 % for the last 10 years (Cherrington, et al., 2013).

In order to build the revenue model to evaluate the financial feasibility of installing a mine water base heating system, the concept of time vale of money was incorporated into the cash flow. NPV (Net Present Value) and IRR (Internal Rate of Return) are the two most widely used investment appraisal methods. NPV and IRR functions come preinstalled with the Microsoft Excel package.

The NPV is a measure that involves a series of cash flows for the whole lifetime of the project, which enables the profits to be foreseen. It adds up the discounting future cash flow (CF), for the whole period (T), before deducting the initial capital investment (*C*), as illustrated in Equation 24 (Abu-Bakar, et al., 2014) The discounted rate, (r_d) chosen for this is selected to be 5%. A positive value of NPV indicates that the investment is feasible while a negative value implies that the investment should be discarded (Sudtharalingam, Hawkes and Green, 2010).

$$NPV=-CF_0+\sum_{n=1}^{20}\frac{CF_T}{(1+r_d)^T} \quad (24)$$

The IRR is another method which also popular and used for evaluating the projects. It can be defined as the growth rate of the project, which is found when the NPV value is equal to zero. In general, the higher the IRR, the more desirable the project becomes. The formula for the IRR is shown in Equation 25.

$$-CF_0+\sum_{n=1}^{20}\frac{CF_T}{(1+IRR)^T}=0 \quad (25)$$

Another commonly used method is the simple payback method. This is used to find out how long does it take to recover the capital investment back. This is a quick method calculate the financial feasibility of the project. Lesser the value of payback, better is the project. In this case, the time value of money is not taken into consideration while evaluating the future cash flows.

$$\text{Payback period}=\frac{\text{Initial Capital Investment}}{\text{Annual profit}} \quad (26)$$

The financial models were used only for the case studies not for the field trials. RHI was not claimed for Markham and Caphouse sites, as these sites were used mainly to test the performance of the heating system and observe, if mine water affected the performance and caused maintenance issues.

4.3 Environmental benefits

The carbon emission rates for different sites are given, the heat pump cannot be considered as a 100 % renewable (unless energy is supplied by a renewable source like solar or wind), as it requires energy to operate the compressor, but a low carbon heating system. The energy consumption of the

GSHP is at least 70 – 30 % (based on the COP of the heat pump) less than the conventional heating system. Table 4.3 shows the emission factors used in the model to calculate the carbon emissions for different fuels.

Table 4.3: Carbon emission factors (DECC, 2015).

Fuel	Carbon emission factor
Grid electricity	0.5331 kg/kWh
Gas	0.1846 kg/kWh

Total carbon savings from GSHP = (total annual energy consumed by gas or electricity ×carbon emission factor) - (total annual electricity consumed by the GSHP × carbon emission factor. (27)

4.4 Summary

This chapter presents a detailed step by step process involved in the design of a mine water based heating system. This includes the technical part, based on the heat demand, the sizing of the heat pump, borehole pump and other accessories required; the financial aspects of calculating the payback period, savings that can be obtained due to the reduction in the operating costs and additional incentives that can be received as RHI payments from the government for using the heat from a GSHP and the environmental benefits that can be obtained due to the reduction in the carbon emissions.

5 Case studies

In this chapter, the case studies of three sites with different heating demand and site configuration are presented. In the case study 1, Chatterley Whitfield, Stoke, is chosen, here the site has an open but flooded shaft with the water fully recovered. In the case study 2, Caphouse colliery, Wakefield, is chosen, here the water is being pumped out continuously. In the case study 3, Markham, is chosen, here the site has an open but flooded shaft with the water at circa 153 mbgl but steadily rising.

5.1 Case study 1. Chatterley Whitfield Enterprise Centre

Chatterley Whitfield Enterprise centre under the Stoke city council is on the former Chatterley Whitfield colliery site. This site has been reclaimed and is converted into an enterprise centre to house 26 offices. The water level in the abandoned coal seams has completely recovered and is just 18 m below ground level. The temperature of the water is circa 12 ^{0}C and offers a potential for harnessing the energy from the flooded mines. This is an opportunity to heat the buildings using the mine and reduce energy consumption and carbon footprint.

5.1.1 Chatterley Whitfield Colliery

The temperature of the water in the flooded mines is around 12 ^{0}C to 20 ^{0}C. The temperature is too low to be used directly for any thermal applications, but by using a heat pump, the low grade energy can be upgraded to a high grade and used for any thermal applications such as heating systems. The large volumes of mine water are available in abandoned workings and heat pumps are considered as an efficient way to heat the buildings. The heat produced from heat pump is eligible to receive financial benefits (Renewable Heat Incentives) from the government (OFGEM, 2016c).

Stoke city region in Staffordshire had a large number of coal mines. Most of the mining operations in the region stopped in the early 1990's and the mines were abandoned. When the mines were active, the water was pumped continuously from underground to keep the seams dry and safe for the people to work underground. Once the mines were abandoned the water pumping operations stopped; the water table started rising to its initial levels and has completely recovered in the region.

The Stoke City Council is now interested in harnessing the energy from the flooded mines. Chatterley Whitfield Enterprise Centre is a reclaimed former mining site and currently has 26 offices. The Hasketh Shaft of the former Chatterley Whitfield mining colliery lies on the site and is still open and gives access to mine water.

5.1.2 Current heating demand

From the previous gas/heating bill of the Enterprise Centre it has been found that, the annual energy demand circa 363,000 kWh with average cost of energy being: £0.0408/kWh.

The building has a peak thermal demand of 90 kW. The heater is run continuously from 7 am to 7 pm.

Figure5.1: Satellite image of the site layout from google maps.

Figure 5.2: The Hasketh Shaft.

Figure 5.3: The Enterprise building.

Figure 5.4: The current boiler room

5.1.3 Current status:

Based on the report on mine water recovery in the Stoke region by Wardell Armstrong, where a pump test and CCTV (Closed circuit Television) tests were carried out and the main findings of the report are as follows:

- The Hasketh Shaft is 651 m deep and blocked at a depth of 284 m.
- The diameter of Hasketh Shaft is 6.09 m.
- The temperature of the water remains constant at circa 12 ^{0}C from a depth of 60 m to 284 m.
- The water has completely recovered and is just 18.1 m below the surface.
- Water can be extracted continuously at the rate of 40 litres per second.

From the above details, the following estimations can be made:

For a maximum flow rate of 40 l/s and 4 ^{0}C (ΔT), the maximum thermal power output that can be extracted is estimated to be 668.8 kW using the following equation:

$$Q = m \times Cp \times \Delta T \quad (28)$$

Where:

m = mass flow rate (kg/s) = volumetric flow rate for water (l s^{-1}) = 40 kg/s.

Q = heat transfer from water (kW).

Cp = volumetric heat capacity of water (4.180 kJ K^{-1} kg^{-1}).

ΔT = total change in temperature (^{o}C) = 4 ^{o}C.

$$Q_{HP} = \frac{COP \times Q}{COP-1} \quad (29)$$

Where, COP is assumed to be 4.

5.1.4 Proposed system

To meet the existing demand of the Chatterley Whitfield Enterprise centre a 90 kW Heat pump with a mine water flow rate of 14.5 m^3/h should be sufficient to meet the entire heating needs of the enterprise building.

A 2 kW borehole pump should be sufficient to meet the flow rate of 14.5 m^3/hr with a 20 m head (Calculated from pump curve data for the pump WPS 12) (WPS Submersible pump, 2016). The power consumption for the heat pump is estimated to be circa 22 kW (from the Danfoss manual for a BW10 090 model) (Danfoss, 2016).

The overall COP of the system is estimated be a minimum of 3.76 (after considering the power consumed by the mine pump).

5.1.5 Cost of installing a new GSHP system

Based on the Enterprise Centre heat demand requirements the cost installing a containerised GSHP system is estimated to be £151,675. The cost of proposed system has been estimated based on the inputs from the suppliers and from the previous experience of building a 20 kW heat pump system at Alkane Energy site at Markham Vale, UK. The breakdown of the costs is as given in the Table 5.1.

Table 5.1 GSHP system installation cost

Item	Cost
Heat Pump + buffer tank	£1,500.00
Heat meters × 2	£6,000.00
Container	£15,000.00
Plumbing + piping	£2,000.00
Mine pump	£5,000.00
Heat exchanger	£10,000.00
Controls	£50,000.00
Trenching	£25,000.00
project management	£1,500.00
Contingency	£17,175.00
Total cost of the system	£151,675.00

5.1.6 Expected savings

The Stoke Council are currently spending circa £14,774.40 per annum for heating the enterprise centre using Natural Gas excluding VAT. Currently the Enterprise Centre buys the Natural Gas at £0.0408 per kWh.

The cost of electricity for a GSHP for an overall COP 3.76 is estimated to be £9,234.00. This would give a savings of £ 4,943.95 per annum. Currently the Enterprise Centre buys electricity at the rate of £0.12 per kWh. The detailed calculation is given the Table 5.2 and Table 5.3.

Table 5.2. GSHP system operations cost.

COP system	3.76	
Heat pump operation time	12	hrs/day
Heat pump peak output	90	kW
Heat pump peak energy output	307,800	kWh/year
GSHP system peak electricity demand	24	kW
GSHP system peak electricity consumption	81,920.45	kWh/year
Energy cost	£9,234	per year

Table 5.3. Natural Gas based boiler operations cost.

Heat demand	307,800	kWh
Efficiency of the boiler	85%	
Actual gas required including the boiler efficiency	362,117.65	kWh
Gas tariff	0.0408	£/kWh
Total cost	14,774.4	£/year

5.1.7 RHI income

Heat pump is classified as a low carbon heating device and is eligible to receive income from the government. For a commercial GSHP the energy generated for the first 1314 hours of peak thermal output, RHI is paid at £0.0895/kWh and the remaining energy usage are paid at £0.0267/kWh. The RHI payment value is coupled to inflation The RHI income for using GSHP for the heating the Enterprise Centre is calculated as £10,640.5 annually. See Table 5.4.

Table 5.4: RHI income.

RHI tier	**Energy in kWh**	**Income**
Tier 1	102492	£10,584.27
Tier 2	239148	£56.23
Total		£10,640.50

Table 5.5: Cash flow.

RPI	3.00%						
Year	Annual operating cost	Savings on heating from GSHP usage	RHI income	Total annual savings including RHI	Total cumulative income including RHI	Total cumulative operating cost	Total cumulative revenue including RHI
0					0	£0.00	-£151,675.00
1	£9,830.45	£4,943.95	£10,640.50	£15,584.45	£15,584.45	£9,830.45	-£136,090.55
2	£10,125.37	£5,092.26	£10,959.72	£16,051.98	£31,636.42	£19,955.82	-£120,038.58
3	£10,429.13	£5,245.03	£11,288.51	£16,533.54	£48,169.96	£30,384.95	-£103,505.04
4	£10,742.00	£5,402.38	£11,627.16	£17,029.54	£65,199.51	£41,126.96	-£86,475.49
5	£11,064.26	£5,564.45	£11,975.98	£17,540.43	£82,739.94	£52,191.22	-£68,935.06
6	£11,396.19	£5,731.39	£12,335.26	£18,066.64	£100,806.58	£63,587.41	-£50,868.42
7	£11,738.08	£5,903.33	£12,705.31	£18,608.64	£119,415.23	£75,325.49	-£32,259.77
8	£12,090.22	£6,080.43	£13,086.47	£19,166.90	£138,582.13	£87,415.71	-£13,092.87
9	£12,452.93	£6,262.84	£13,479.07	£19,741.91	£158,324.04	£99,868.63	£6,649.04
10	£12,826.51	£6,450.73	£13,883.44	£20,334.17	£178,658.20	£112,695.14	£26,983.20
11	£13,211.31	£6,644.25	£14,299.94	£20,944.19	£199,602.40	£125,906.45	£47,927.40
12	£13,607.65	£6,843.58	£14,728.94	£21,572.52	£221,174.91	£139,514.10	£69,499.91
13	£14,015.88	£7,048.88	£15,170.81	£22,219.69	£243,394.61	£153,529.98	£91,719.61
14	£14,436.35	£7,260.35	£15,625.93	£22,886.28	£266,280.89	£167,966.33	£114,605.89
15	£14,869.44	£7,478.16	£16,094.71	£23,572.87	£289,853.76	£182,835.78	£138,178.76
16	£15,315.53	£7,702.51	£16,577.55	£24,280.06	£314,133.82	£198,151.31	£162,458.82
17	£15,774.99	£7,933.58	£17,074.88	£25,008.46	£339,142.28	£213,926.30	£187,467.28
18	£16,248.24	£8,171.59	£17,587.13	£25,758.71	£364,901.00	£230,174.54	£213,226.00
19	£16,735.69	£8,416.74	£18,114.74	£26,531.48	£391,432.47	£246,910.23	£239,757.47
20	£17,237.76	£8,669.24	£18,658.18	£27,327.42	£418,759.89	£264,148.00	£267,084.89

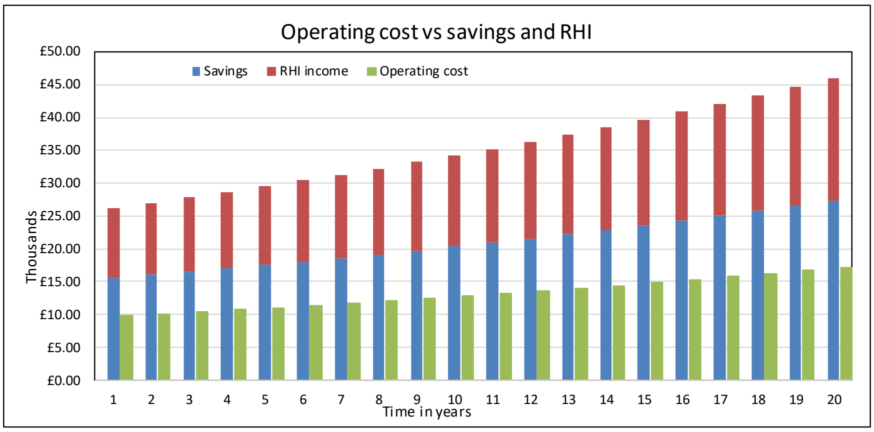


Figure 5.5: Operating cost, savings and RHI income.

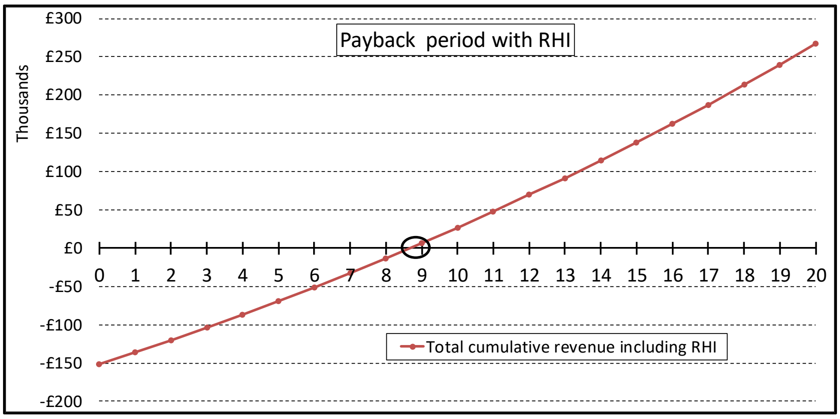


Figure 5.6: Payback period Chatterley Whitfield, Stoke.

Table 5.6: IRR and NPV.

	IRR			NPV, discount 5 %	
Year	Total annual profit including RHI	Total annual profit excluding RHI	Year	Total annual profit excluding RHI	Total annual profit including RHI
0	-£151,675.00	-£151,675.00	0	-£151,675.00	-£151,675.00
1	£15,584.45	£4,943.95	1	£4,943.95	£15,584.45
2	£16,051.98	£5,092.26	2	£5,092.26	£16,051.98
3	£16,533.54	£5,245.03	3	£5,245.03	£16,533.54
4	£17,029.54	£5,402.38	4	£5,402.38	£17,029.54
5	£17,540.43	£5,564.45	5	£5,564.45	£17,540.43
6	£18,066.64	£5,731.39	6	£5,731.39	£18,066.64
7	£18,608.64	£5,903.33	7	£5,903.33	£18,608.64
8	£19,166.90	£6,080.43	8	£6,080.43	£19,166.90
9	£19,741.91	£6,262.84	9	£6,262.84	£19,741.91
10	£20,334.17	£6,450.73	10	£6,450.73	£20,334.17
11	£20,944.19	£6,644.25	11	£6,644.25	£20,944.19
12	£21,572.52	£6,843.58	12	£6,843.58	£21,572.52
13	£22,219.69	£7,048.88	13	£7,048.88	£22,219.69
14	£22,886.28	£7,260.35	14	£7,260.35	£22,886.28
15	£23,572.87	£7,478.16	15	£7,478.16	£23,572.87
16	£24,280.06	£7,702.51	16	£7,702.51	£24,280.06
17	£25,008.46	£7,933.58	17	£7,933.58	£25,008.46
18	£25,758.71	£8,171.59	18	£8,171.59	£25,758.71
19	£26,531.48	£8,416.74	19	£8,416.74	£26,531.48
20	£27,327.42	£8,669.24	20	£8,669.24	£27,327.42
IRR %	11%	-1%	NPV total value	-£69,281.89	£92,502.19

5.1.8 Payback period

From the Table 5.5, Table 5.6 and Figure 5.6, it is clear that the payback period will be less than 9 years with RHI income. Both IRR and NPV are negative without the RHI and hence the project is not financially viable without RHI. Both NPV (discount rate of 5% is considered based on the input from the company) and IRR are calculated using the inbuilt function in MS Excel, where the annual profits and discount rate for NPV is given as input.

5.1.9 Carbon Emissions

By using the GSHP system the carbon emissions would be reduced to 41,022 kg (36% less) annually from the current levels of 66,829 kg annually.

Table 5.7: Carbon Emission.

With Natural Gas	66,829	kg p.a
With Heat Pump	41,022	kg p.a
Savings	28,810	kg p.a
Savings in %	36%	

5.1.10 Conclusion

For the current heat demand, a single shaft (extraction and discharge from the same shaft) would be feasible. The water level has recovered, therefore the cost of pumping the water from the ground would be low and a high overall efficiency (COP) can be obtained. Along with the savings in operating cost, savings in carbon emissions can also be obtained. The project will be economically feasible only if the RHI income is obtained.

5.2 Case study 2. National Coal Mining Museum, Caphouse, UK

National Coal-Mining Museum (NCM) is on the site of former Caphouse colliery. This former colliery site has been converted into a mining museum, where the public is allowed to visit the underground galleries. The water from the shaft is continuously pumped and treated to remove the impurities, before discharging the water into Calder river. The temperature of the water is circa 12 ^{0}C and offers a potential for harnessing the energy from the flooded mines and heat the buildings of the museum.

5.2.1 Caphouse colliery

The Caphouse colliery was opened in 1830 and coal was extracted from here until its closure in 1985. It was converted into a museum and opened to public in the year 1988, where the public have a chance to visit the underground galleries. In order to keep the underground galleries, dry the water is continuously pumped at a rate of circa 30 litres per second. The water is partially oxygenated in the shaft and is treated to remove all the effluents before it is discharged into the river Calder. More details of the site and mine water are mentioned in a Chapter 5.

5.2.2 Current heating demand

The main museum building consists of visitor centre with a café, gift centre and library and conference room. It has a combined head demand of 650 kW. The heater is run continuously from 8 am to 6 pm.

5.2.3 Current status:

- The water is continuously pumped at a rate of circa 30 litres per second to keep the underground galleries dry.

- The water has an iron content of circ15 mg/l.
- The water is pumped continuously for 24 hours a day during winter months and for about 15 hours a day during summer months.

For a maximum flow rate of 30 l/s and 4 ^{0}C (ΔT), the maximum heat that can be extracted from mine water, the thermal output is estimated to be 668.8 kW, sufficient to meet the demands of the visitor centre.

Using the following equation:

$$Q = m \times Cp \times \Delta T \tag{30}$$

Where:

m = mass flow rate (kg/s) = volumetric flow rate for water (l s^{-1}) = 30 kg/s

Q = heat transfer from water (kW)

Cp = volumetric heat capacity of water (4.180 kJ K^{-1} kg^{-1})

ΔT = total change in temperature (^{o}C) = 4 ^{o}C

$$Q_{HP} = \frac{COP \times Q}{COP-1} \tag{31}$$

Where, COP is assumed to be 4

5.2.4 Proposed system

To meet the existing demand a 650 kW Heat pump with a mine water flow rate of circa 29.5 litres per should be sufficient to meet the entire heating needs of the visitor centre building.

Since the water is already pumped, there are no additional costs and COP of the heat pump is equal to that of the whole system.

5.2.5 Cost of installing a new GSHP system

Based on the estimation of the contractors the cost installing a GSHP system is estimated to be £693,250.0. The breakdown of the costs is as given in the Table 5.8. The costs have been taken based on the actual quotes from the suppliers.

Table 5.8: GSHP system installation cost.

Item	Cost
Heat Pump + buffer tank	£70,000
Heat meters × 2	£4,000.00
Container	£20,000.00
Plumbing + piping	£50,000.00
Mine pump	0
Heat exchanger	£40,000.00
Controls	£20,000.00
Trenching	£320,000.00
project management	£100,000.00
Contingency	£69.250.
Total cost of the system	£693,250.00

5.2.6 Expected savings

The museum is spending circa £76,470 per annum for heating the enterprise centre using Natural Gas excluding VAT at peak load of 650 kW. Currently museum buys the Natural Gas at £0.040/kWh

The annual cost of electricity for a GSHP with an overall COP 4 is estimated to be £48,750. This would give savings of £24,375 per annum. Currently the Enterprise Centre buys electricity at the rate of £0.12/kWh. The detailed calculation is given the Table 5.9 and Table 5.10.

Table 5.9: GSHP system operations cost.

COP system	4	
Heat pump operation time	12	hrs/day
Heat pump peak output	650	kW
Heat pump peak energy output	1,625,000.00	kWh/year
GSHP system peak electricity demand	162.5	kW
GSHP system peak electricity consumption	406,250.00	kWh/year
Energy cost	£48,750	per year

Table 5.10: Natural Gas based boiler operations cost.

Heat demand	1,625,000.00	kWh
Efficiency of the boiler	85%	
Actual gas required assuming boiler efficiency	1,911,764.71	kWh
Cost of gas	0.0400	£/kWh
Total cost	76,470.59	£/year

5.2.7 RHI income

Utilisation of heat from the Heat pump is classified as a low carbon technology and is eligible to receive income from the government. For a commercial GSHP the first 1314 hours of the rated size RHI is paid at £0.0895/kWh and the remaining hours are paid at £0.0267/kWh. The RHI income for using GSHP for the heating the Enterprise Centre is calculated as £10,640.5 annually and is coupled to inflation.

Table 5.11: RHI income.

RHI tier	**Energy in kWh**	**Income**
Tier 1	854,100.00	£76,441.95
Tier 2	1,186.00	£31.67
Total		£ 76,473.62

Table 5.12: Cash flow.

	RPI	3.00%					
Year	Annual operating cost	Savings on heating from GSHP usage	RHI income	Total annual savings including RHI	Total cumulative income including RHI	Total cumulative operating cost	Total cumulative revenue including RHI
0					£0.00	£0.00	-£693,250.00
1	£48,750.00	£27,720.59	£76,473.62	£104,194.20	£104,194.20	£48,750.00	-£589,055.80
2	£50,212.50	£28,552.21	£78,767.82	£107,320.03	£211,514.24	£98,962.50	-£481,735.76
3	£51,718.88	£29,408.77	£81,130.86	£110,539.63	£322,053.87	£150,681.38	-£371,196.13
4	£53,270.44	£30,291.04	£83,564.79	£113,855.82	£435,909.69	£203,951.82	-£257,340.31
5	£54,868.55	£31,199.77	£86,071.73	£117,271.50	£553,181.18	£258,820.37	-£140,068.82
6	£56,514.61	£32,135.76	£88,653.88	£120,789.64	£673,970.82	£315,334.98	-£19,279.18
7	£58,210.05	£33,099.83	£91,313.50	£124,413.33	£798,384.15	£373,545.03	£105,134.15
8	£59,956.35	£34,092.83	£94,052.90	£128,145.73	£926,529.88	£433,501.38	£233,279.88
9	£61,755.04	£35,115.61	£96,874.49	£131,990.10	£1,058,519.98	£495,256.42	£365,269.98
10	£63,607.69	£36,169.08	£99,780.72	£135,949.80	£1,194,469.78	£558,864.12	£501,219.78
11	£65,515.92	£37,254.15	£102,774.15	£140,028.30	£1,334,498.08	£624,380.04	£641,248.08
12	£67,481.40	£38,371.78	£105,857.37	£144,229.15	£1,478,727.23	£691,861.44	£785,477.23
13	£69,505.84	£39,522.93	£109,033.09	£148,556.02	£1,627,283.25	£761,367.28	£934,033.25
14	£71,591.02	£40,708.62	£112,304.08	£153,012.70	£1,780,295.95	£832,958.30	£1,087,045.95
15	£73,738.75	£41,929.88	£115,673.21	£157,603.08	£1,937,899.04	£906,697.05	£1,244,649.04
16	£75,950.91	£43,187.77	£119,143.40	£162,331.18	£2,100,230.21	£982,647.96	£1,406,980.21
17	£78,229.44	£44,483.41	£122,717.70	£167,201.11	£2,267,431.32	£1,060,877.40	£1,574,181.32
18	£80,576.32	£45,817.91	£126,399.24	£172,217.14	£2,439,648.47	£1,141,453.72	£1,746,398.47
19	£82,993.61	£47,192.45	£130,191.21	£177,383.66	£2,617,032.12	£1,224,447.34	£1,923,782.12
20	£85,483.42	£48,608.22	£134,096.95	£182,705.17	£2,799,737.29	£1,309,930.76	£2,106,487.29

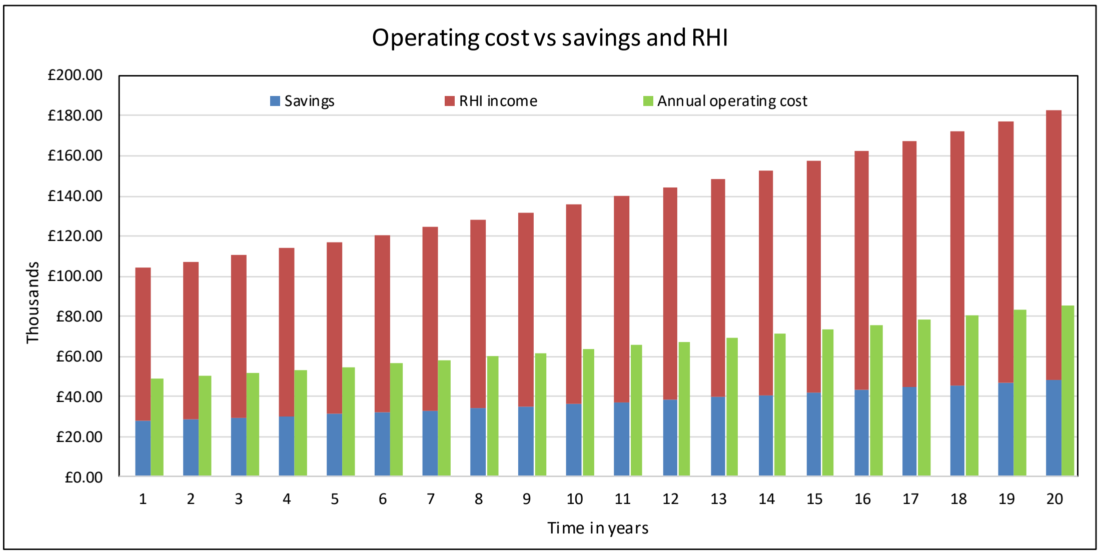


Figure:5.7. Operating cost, savings and RHI income.

.

Table 5.13: IRR and NPV.

	IRR			NPV, discount 5 %	
Year	Total cumulative revenue including RHI	Total cumulative revenue excluding RHI	Year	Total cumulative revenue excluding RHI	Total cumulative revenue including RHI
0	-£693,250.00	-£693,250.00	0	-£693,250.00	-£693,250.00
1	£104,194.20	£27,720.59	1	£27,720.59	£104,194.20
2	£107,320.03	£28,552.21	2	£28,552.21	£107,320.03
3	£110,539.63	£29,408.77	3	£29,408.77	£110,539.63
4	£113,855.82	£30,291.04	4	£30,291.04	£113,855.82
5	£117,271.50	£31,199.77	5	£31,199.77	£117,271.50
6	£120,789.64	£32,135.76	6	£32,135.76	£120,789.64
7	£124,413.33	£33,099.83	7	£33,099.83	£124,413.33
8	£128,145.73	£34,092.83	8	£34,092.83	£128,145.73
9	£131,990.10	£35,115.61	9	£35,115.61	£131,990.10
10	£135,949.80	£36,169.08	10	£36,169.08	£135,949.80
11	£140,028.30	£37,254.15	11	£37,254.15	£140,028.30
12	£144,229.15	£38,371.78	12	£38,371.78	£144,229.15
13	£148,556.02	£39,522.93	13	£39,522.93	£148,556.02
14	£153,012.70	£40,708.62	14	£40,708.62	£153,012.70
15	£157,603.08	£41,929.88	15	£41,929.88	£157,603.08
16	£162,331.18	£43,187.77	16	£43,187.77	£162,331.18
17	£167,201.11	£44,483.41	17	£44,483.41	£167,201.11
18	£172,217.14	£45,817.91	18	£45,817.91	£172,217.14
19	£177,383.66	£47,192.45	19	£47,192.45	£177,383.66
20	£182,705.17	£48,608.22	20	£48,608.22	£182,705.17
IRR %	17%	1%	NPV total value	-£238,758.87	£923,988.49

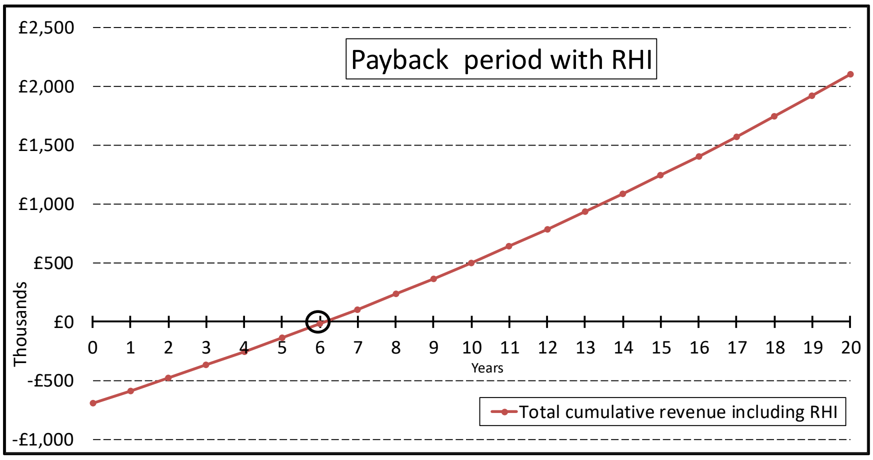


Figure 5.8: Payback period.

5.2.8 Payback period

From the Table 21 and Figure 5.6, it is clear that the payback period will be less than 7 years with RHI income and the project is not economically feasible without the RHI income. NPV is negative and IRR is 1% without the RHI. Both NPV (discount rate of 5% is considered based on the input from the company) and IRR are calculated using the inbuilt function in MS Excel, where the annual profits and discount rate for NPV is given as input.

5.2.9 Carbon Emissions

By using the GSHP system, the carbon emissions can be reduced to 216 tonnes (39% less) annually from the current levels of 352 tonnes annually.

Table 5.14: Carbon Emissions.

With Natural Gas	352	tonnes p.a
With Heat Pump	216	tonnes p.a
savings	136	tonnes p.a
Savings (%)	39%	

5.2.10 Conclusion:

For the current heat demand, a single shaft (extraction and discharge from the same shaft) would be feasible. The water level has recovered, therefore the cost of pumping the water from the ground would be less and a high overall efficiency (COP) can be obtained. Along with the savings in operating cost, savings in carbon emissions can also be obtained. Without the RHI incentive the project is not economically viable.

5.3 Case study 3. Alkane Energy, Markham

Alkane Energy currently occupy the former Markham colliery site and have an existing open mine shaft which is flooded. Alkane Energy have their control centre and maintenance depot at the site and it is operated 24 × 7. The office block and the storeroom are currently heated using the water from mine water using a GSHP of 20 kW thermal output. Alkane Energy plan to extend the current site with new infrastructure and also intend to heat the new infrastructure using mine water and GSHP. The overall heat demand of the site once the new buildings are in place is estimated to be 46 kW. Hence, an additional heat pump is required to meet the demand and existing borehole pump is sufficient to meet the additional water flow rate required. The existing container and most of the infrastructure is already in place. Detailed information about the site and layout is mentioned in Chapter 6.

5.3.1 Current heating demand

The annual energy demand circa 309,120 kWh with average cost of electricity being: £0.12/kWh.

The building has a peak thermal demand of 46 kW. The heater is run continuously24 × 7.

5.3.2 Proposed system

To meet the demand, a 46 kW Heat pump (additional heat pump of 26 kW is required) with a mine water flow rate of at least 7.43 m^3/h is required.

The overall COP of the system is estimated be a minimum of 2.69 (after considering the power consumed by the mine pump). Overall COP will increase as the water level rises.

5.3.3 Cost of installing a new GSHP system

Most of the infrastructure needed are already in place an additional heat pump, buffer tank, heat exchanger and other small accessories are needed. The breakdown of the costs is as given in the Table 5.15. The costs are based on the actual quote from the suppliers.

Table 5.15: GSHP system installation cost.

Item	**Cost**
Heat Pump + buffer tank	£1,500.00
heat meters × 2	£0.00
Container	£10,000.00
Plumbing + piping	£0.00
Mine pump	£3,000.00
Heat exchanger	£5,000.00
Controls	£0.00
Trenching	£10,000.00
project management	£1,500.00
contingency	£4,425.00
Total Cost of the system	£53,925.00

5.3.4 Expected savings

The annual heating demand is expected to be around circa 309,120 kWh per annum. Alkane Energy buys electricity at the rate of £0.12/kWh

The cost of electricity for a GSHP of an overall COP 2.69 is estimated to be £13,766.19. This would give savings of £23,184per annum. The detailed calculation is given below in Table 5.16.

Table 5.16: GSHP system operations cost.

COP system	2.69	
Heat pump operation time	24	hrs/day
Heat pump peak output	46	kW
Heat pump peak energy output	309,120	kWh/year
System peak electricity consumption	114,718.28	kWh/year
Energy cost	£13,766.19	per year

Table 5.17: Electric heater operations cost.

Heat demand	309,120	kWh
Efficiency of heater	100%	
Cost of electricity	£0.12	per kWh
Total cost	£37,094.40	per annum

5.3.5 RHI income

Utilisation of heat from the Heat pump is classified as a low carbon technology and is eligible to receive income from the government. For a commercial GSHP the first 1314 hours of the rated size RHI is paid at £0.0895/kWh and the remaining hours are paid at £0.0267/kWh. The RHI income for using GSHP for heating the proposed Alkane Energy buildings is calculated as £5,554.08 annually and it is coupled to inflation.

Table 5.18: RHI income.

RHI tier	Energy in kWh	Income
Tier 1	59130	£5,409.74
Tier 2	3486	£144.34
Total		£5,554.08

Table 5.19: Cash flow.

	RPI	3.00%					
Year	Annual operating cost	Savings on heating from GSHP usage	RHI income	Total annual savings including RHI	Total cumulative income including RHI	Total cumulative operating cost	Total cumulative revenue including RHI
0					0	£0.00	-£53,925.00
1	£13,766.19	£23,184.00	£5,554.08	£28,738.08	£28,738.08	£13,766.19	-£25,186.92
2	£14,179.18	£23,879.52	£5,720.70	£29,600.22	£58,338.30	£27,945.37	£4,413.30
3	£14,604.55	£24,595.91	£5,892.32	£30,488.23	£88,826.53	£42,549.93	£34,901.53
4	£15,042.69	£25,333.78	£6,069.09	£31,402.87	£120,229.40	£57,592.62	£66,304.40
5	£15,493.97	£26,093.80	£6,251.16	£32,344.96	£152,574.36	£73,086.59	£98,649.36
6	£15,958.79	£26,876.61	£6,438.70	£33,315.31	£185,889.67	£89,045.38	£131,964.67
7	£16,437.55	£27,682.91	£6,631.86	£34,314.77	£220,204.44	£105,482.94	£166,279.44
8	£16,930.68	£28,513.40	£6,830.82	£35,344.21	£255,548.65	£122,413.62	£201,623.65
9	£17,438.60	£29,368.80	£7,035.74	£36,404.54	£291,953.19	£139,852.22	£238,028.19
10	£17,961.76	£30,249.86	£7,246.81	£37,496.67	£329,449.86	£157,813.98	£275,524.86
11	£18,500.61	£31,157.36	£7,464.22	£38,621.57	£368,071.43	£176,314.59	£314,146.43
12	£19,055.63	£32,092.08	£7,688.14	£39,780.22	£407,851.66	£195,370.22	£353,926.66
13	£19,627.30	£33,054.84	£7,918.79	£40,973.63	£448,825.28	£214,997.52	£394,900.28
14	£20,216.12	£34,046.49	£8,156.35	£42,202.84	£491,028.12	£235,213.64	£437,103.12
15	£20,822.60	£35,067.88	£8,401.04	£43,468.92	£534,497.04	£256,036.24	£480,572.04
16	£21,447.28	£36,119.92	£8,653.07	£44,772.99	£579,270.03	£277,483.52	£525,345.03
17	£22,090.70	£37,203.51	£8,912.67	£46,116.18	£625,386.21	£299,574.22	£571,461.21
18	£22,753.42	£38,319.62	£9,180.05	£47,499.66	£672,885.87	£322,327.64	£618,960.87
19	£23,436.02	£39,469.21	£9,455.45	£48,924.65	£721,810.53	£345,763.67	£667,885.53
20	£24,139.10	£40,653.28	£9,739.11	£50,392.39	£772,202.92	£369,902.77	£718,277.92

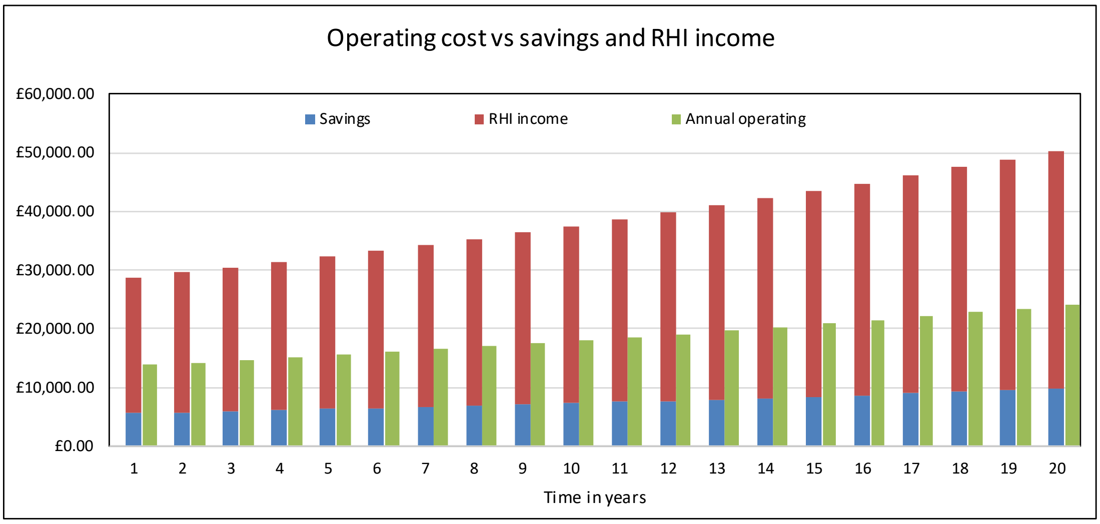


Figure 5.9: Operating cost and income due to the savings and RHI

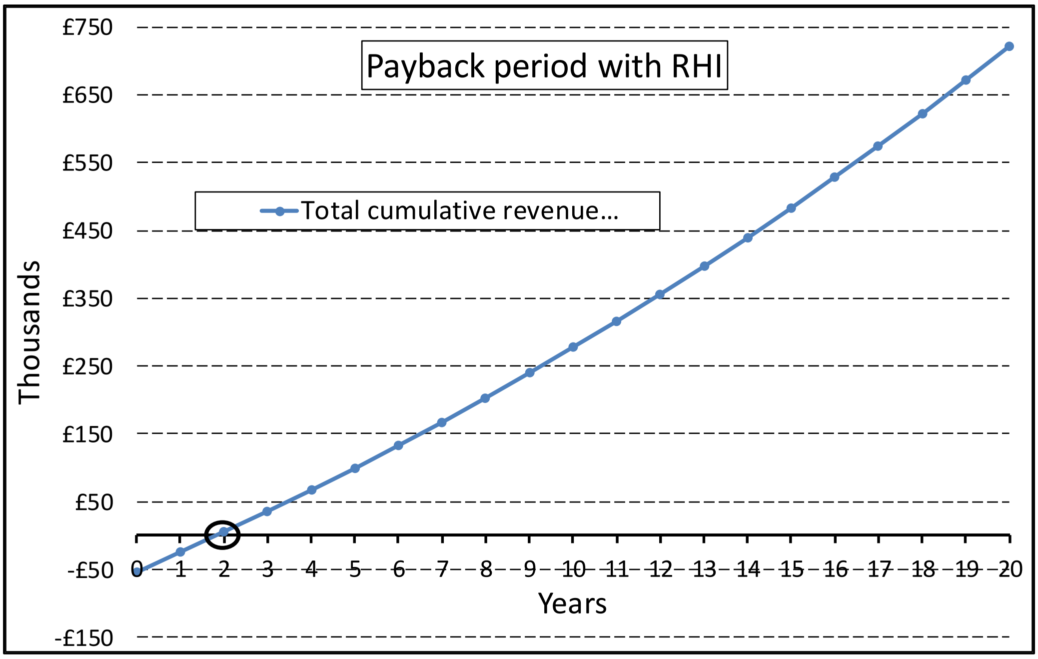


Figure 5.10: Payback period.

Table 5.20.IRR and NPV.

	IRR			NPV, discount 5 %	
Year	Total cumulative revenue including RHI	Total cumulative revenue excluding RHI	Year	Total cumulative revenue excluding RHI	Total cumulative revenue including RHI
0	-£53,925.00	-£53,925.00	0	-£53,925.00	-£53,925.00
1	£28,738.08	£23,184.00	1	£23,184.00	£28,738.08
2	£29,600.22	£23,879.52	2	£23,879.52	£29,600.22
3	£30,488.23	£24,595.91	3	£24,595.91	£30,488.23
4	£31,402.87	£25,333.78	4	£25,333.78	£31,402.87
5	£32,344.96	£26,093.80	5	£26,093.80	£32,344.96
6	£33,315.31	£26,876.61	6	£26,876.61	£33,315.31
7	£34,314.77	£27,682.91	7	£27,682.91	£34,314.77
8	£35,344.21	£28,513.40	8	£28,513.40	£35,344.21
9	£36,404.54	£29,368.80	9	£29,368.80	£36,404.54
10	£37,496.67	£30,249.86	10	£30,249.86	£37,496.67
11	£38,621.57	£31,157.36	11	£31,157.36	£38,621.57
12	£39,780.22	£32,092.08	12	£32,092.08	£39,780.22
13	£40,973.63	£33,054.84	13	£33,054.84	£40,973.63
14	£42,202.84	£34,046.49	14	£34,046.49	£42,202.84
15	£43,468.92	£35,067.88	15	£35,067.88	£43,468.92
16	£44,772.99	£36,119.92	16	£36,119.92	£44,772.99
17	£46,116.18	£37,203.51	17	£37,203.51	£46,116.18
18	£47,499.66	£38,319.62	18	£38,319.62	£47,499.66
19	£48,924.65	£39,469.21	19	£39,469.21	£48,924.65
20	£50,392.39	£40,653.28	20	£40,653.28	£50,392.39
IRR %	56%	46%	NPV total value	£301,145.28	£385,592.57

5.3.6 Payback period

From the Table 27, it is clear that the payback period will be less than 2 years with RHI income. This project is feasible even without the RHI as the GSHP is competing with electricity and both NPV and IRR are positive even without the RHI. Both NPV (discount rate of 5% is considered based on the input from the company) and IRR are calculated using the inbuilt function in MS Excel, where the annual profits and discount rate for NPV is given as input

5.3.7 Carbon Emissions

By using the GSHP system the carbon emissions can be reduced to 123.59 tonnes (75% less) annually from the levels of 164.79 tonnes annually.

Table 5.21.Carbon Emission

With Electric heater	164.79	tonnes p.a
With Heat Pump	41.198	tonnes p.a
Savings	123.59	kg p.a
Savings in %	75%	

5.3.8 Conclusion

For the proposed heat demand, most of the existing infrastructure can be used and the hence capital cost will also be less. The water level is rising steadily and therefore the cost of pumping the water from the ground would also reduce overtime and a higher overall efficiency (COP) can be obtained. Along with the savings in operating cost, savings in carbon emissions can also be obtained.

6 Experimental Work

In order to test theoretical concept practically in field and observe performance of the system, two pilot plants with different site configurations are built at Markham and at Caphouse and the experimental trails are carried out. At Markham, the warm water is pumped and spent water is discharged into an abandoned and flooded mineshaft. The water is pumped using a borehole pump. Additional energy is required to pump the water to the surface and hence the pumping depth has an impact on the overall efficiency of the system. At Caphouse, the water is already being pumped out and treated before discharging it to the river. The pilot plant uses a small amount of raw mine water before it is treated. Since no additional energy is required for the pumping, the total efficiency of the system is nearly equal to that of the heat pump. The pilot plant plants serve as a good measure and observe any maintenance problems that mine water can cause.

6.1 Markham Pilot Plant

Markham Colliery was one of the largest collieries in UK and operated from 1904 until its closure in 1993. Like many areas in the midlands and northern part of England, it is underlain by the coal mines. In order to regenerate the area, following the mine closures, the government has planned the Markham Vale enterprise region to convert this region into a commercial and industrial hub and attract new investment. To precipitate the new regeneration plan, a new junction 29A was constructed on the M1 motorway to give access to Markham Vale. Markham Vale is a 200-acre development site located at the new Junction 29A of the M1 Motorway. According to the Markham Vale website, ‘The man aspiration of the council is to be the greenest business park in the UK, employing innovative technologies to deliver very low emission levels’ (Derbyshire County Council, 2016).

Figure 6.1: Markham Vale Development region (Derbyshire county council, 2016).

Alkane Energy occupy a site right in the heart of the proposed Markham Vale, and have in the past extracted coal mine methane from the open Markham No.3 shaft for the generation of electricity by passing the methane gas through gas engines. The shaft became flooded in 2006 and cut all the underground connections through which the gas was flowing and thereby making the site less useful. Later on, the engines at the site were converted to operate on STOR (Short Term Operating Reserve) electricity generation using the mains gas. Under STOR operations, the engines are only operated if there is shortage of electricity available to the National Grid, where National Grid pays a premium price to buy electricity from independent generators like Alkane Energy. Alkane Energy also have their control centre and maintenance depot at the site and were using electrical heater to heat the buildings.

A mine water based pilot plant is constructed to use the warm mine water in the Shaft number 3 and use it to heat the office block and the store room using a Ground Source Heat Pump (GSHP). Experimental work is carried out to test the feasibility of using mine water for space heating.

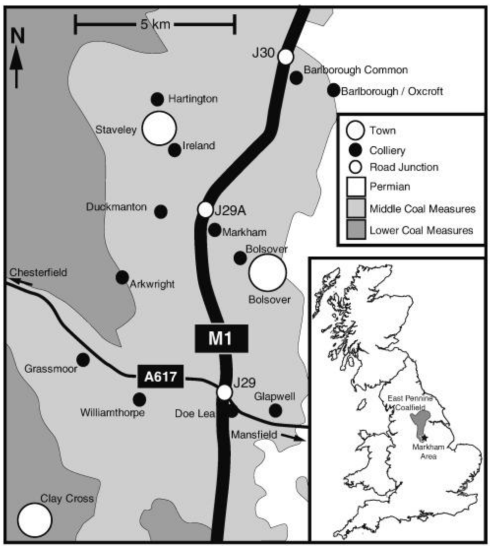


Figure 6.2: Geological setting of the Markham region ('Burnside, et al., 2016).

6.1.1 Markham Colliery History and Configuration

Markham Colliery, located just north of Bolsover, Derbyshire, UK, comprises four main shafts. The site (1.3285°W 53.2424°N) see Figure 6.2. Three of those shafts were filled and capped. Two shafts (shafts No. 2 and 3) is now on the land occupied Alkane Energy. Since 1904, Markham colliery worked coal from a number of seams of the Westphalian Lower and Middle Coal Measures strata (Sheppard, 2005). Markham No. 3 shaft is the only one of the shafts that has not been backfilled, following abandonment in 1993. The shaft was brick-lined at 15 feet (4.6 m) diameter and was reportedly c. 490 m deep (HealeyHero, 2016). Shaft no. 1 and 4, with which shaft no. 3 interconnected, reached the Blackshale coal at c. 630 m deep ('Burnside, et al., 2016). Markham colliery is part of a wider network of hydraulically interlinked abandoned collieries, including those at Arkwright (53.2296°N 1.3633°W), Bolsover (53.2350°N 1.3116°W), Duckmanton (53.2447°N 1.3521°W) and Ireland, Staveley (53.2626°N 1.3456°W). Markham No 3 Shaft was left largely open, following abandonment, with a hydraulically open plug at the level of the Ell seam (-357 m asl), to allow venting of mine gas, see Figure 6.3.

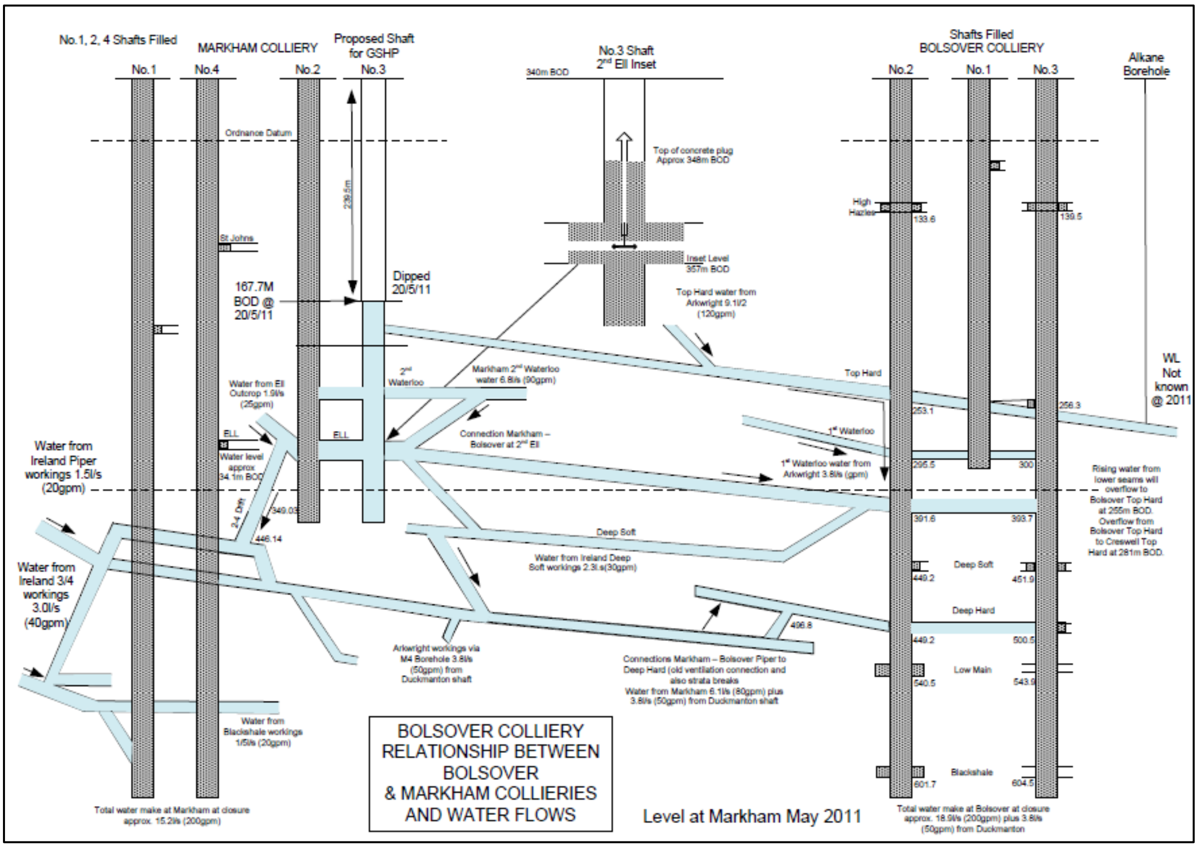


Figure 6.3: Coal seam interconnections in Markham. This images is sourced from Alkane Energy UK.

See Figure 6.4, to see the rate of rise of mine water, in May 2011, the water level was 239.5 mbgl (-167.7 m asl), while by February 2016 it was at 136 mbgl.

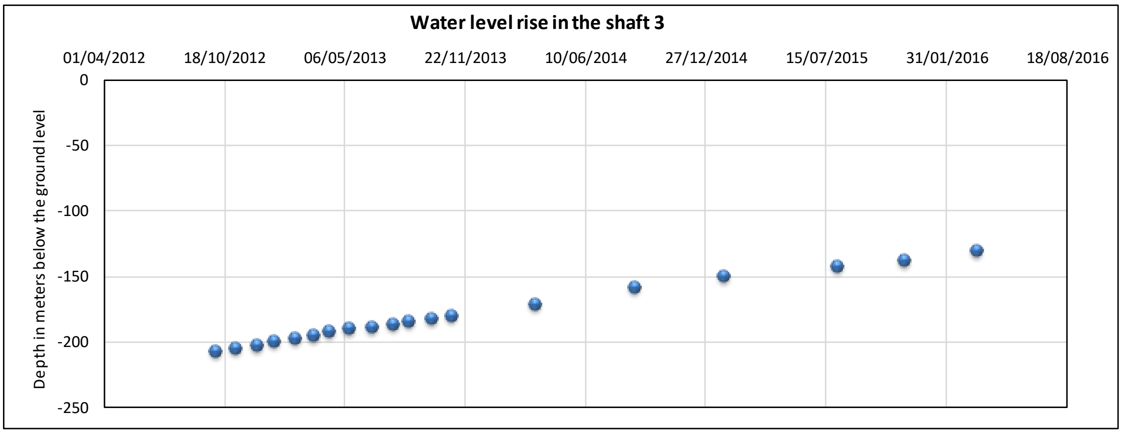


Figure 6.4: Raise in mine water level in the shaft.

6.1.2 GSHP pilot plant

A pilot plant of size 20 kW thermal output is installed at Alkane Energy site at Markham. The GSHP is used to heat the control centre and the maintenance depot of Alkane Energy and the site requires heating 24×7. The system is designed to extract warm water from the abandoned mine shaft and inject a slightly colder spent water back into the same shaft, and the heat pump is used to upgrade the low grade heat of mine water into a higher grade heat and utilise this high grade heat to heat the office buildings of the Alkane Energy at Markham. Recently the GSHP was used to pre-warm one of the standby gas engine as well. The schematic of the system is given the Figure 6.6. The office building uses three different kinds of emitter systems to heat the buildings, they include wet radiator units, fan coil units and under floor heating systems.

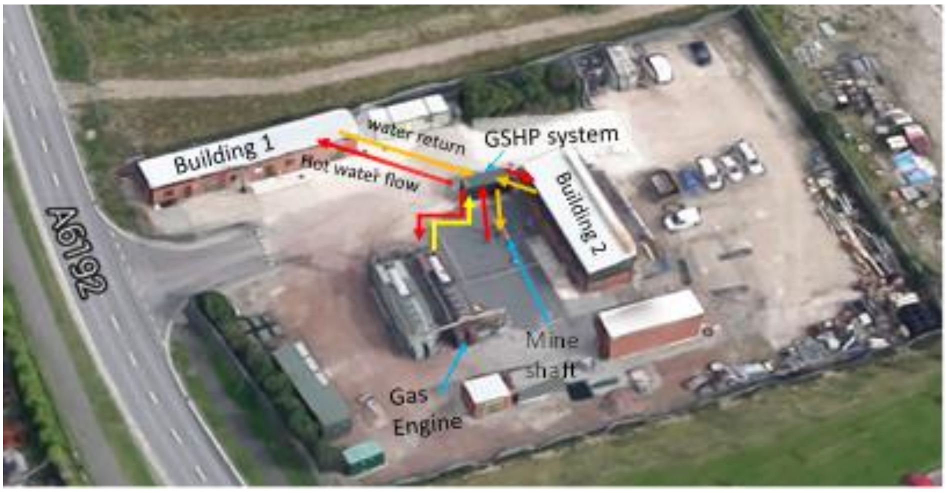


Figure 6.5: Aerial view of site from google maps.

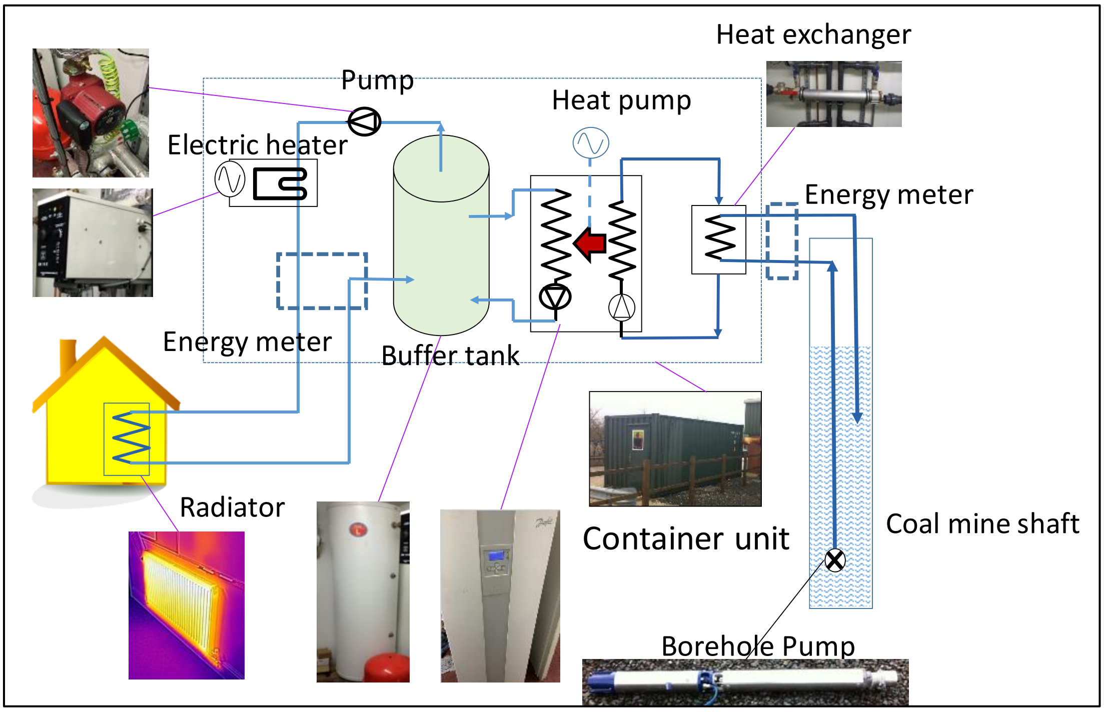


Figure 6.6: Schematic of the Markham system.

6.1.3 Description of the system compnents

The schematic of the pilot plant is as shown in Figure 6.6. It consists of a commercial 20 kW_{th} Danfoss heat pump, two counter flow shell and tube type heat exchangers of 12.5 kW capacity each, a 300 litre buffer tank, mesh filter and pipes connecting all the units are fitted in a 20 feet modified container. The container also houses the control panel for the borehole pump. A 11 kW borehole pump is installed at a depth of 170 m and return diffuser at a depth of 153 m below the ground level. As a safety mechanism, the methane in the mineshaft is monitored and would trip the system if the methane level crosses 1.75 %.

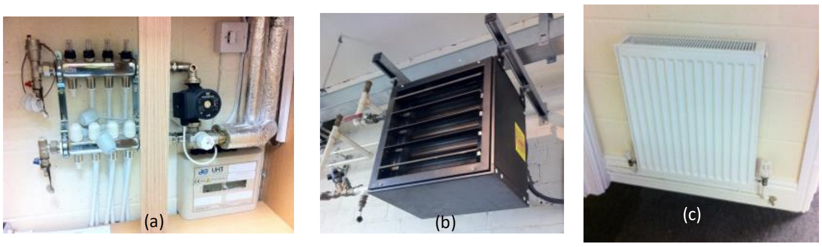


Figure 6.7: The Emitter systems used to dissipate the heat.

Figure 6.8: Mine water flow and return pipe.

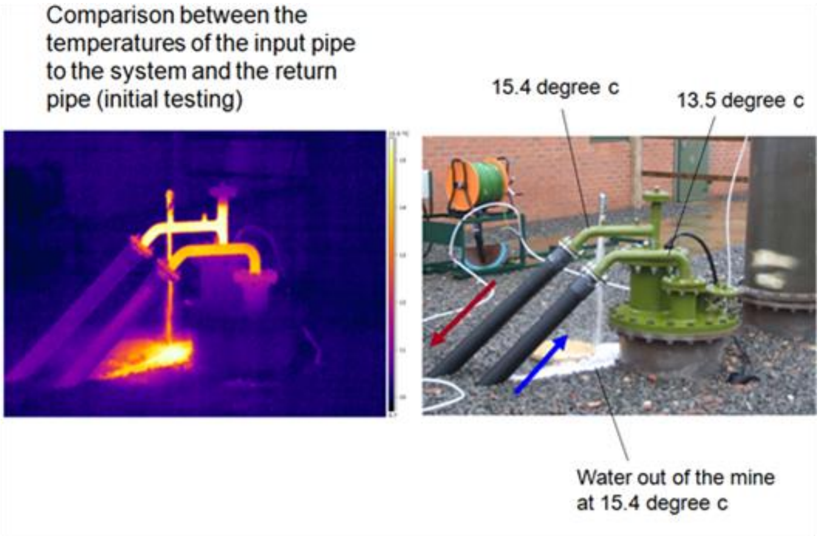


Figure 6.9. Thermographic image of mine water flow and return.

Figure 6.10: (a) Filter.(b) Heat exchanger.

Figure 6.11: (a) Heat pump. (b) Buffer tank.

6.1.4 Instrumentation and monitoring system

The energy meters are installed to measure the electricity consumption of heat pump and borehole pump. KAMSTRUP Multical 602 heat meters are used to monitor both mine water and the heat pump hot water parameters. The heat meter measures the flow rate in m^3/hr, ∆T of the water in degree C, instantaneous power in kW and cumulative energy in MWh. The KAMSTRUP Multical 602 consists of an integrated flow and temperature sensors and an integrator to calculate the energy based on the flow and temperature values.

The entire monitoring system is connected to a telemetry system; all the devices send the data in Modbus protocol to a redlion unit.

Figure 6.12: Data monitoring and acquisition unit.

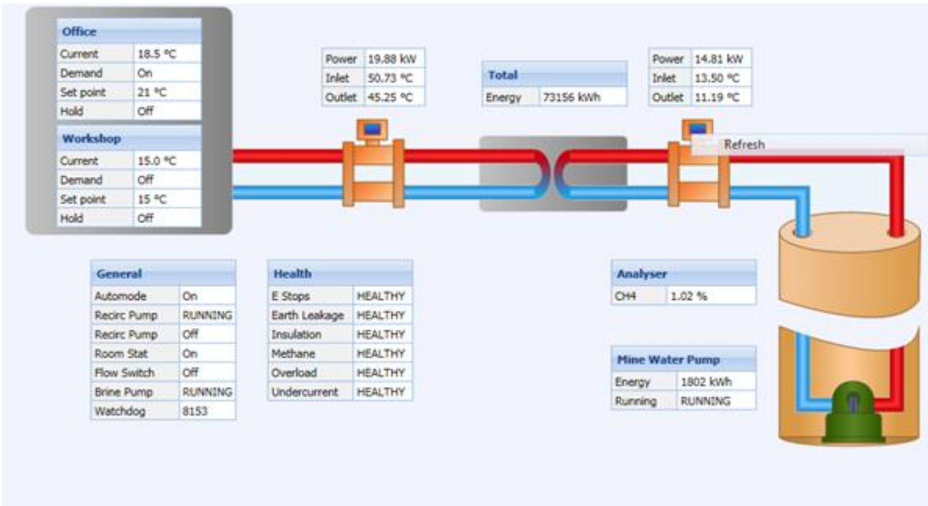


Figure 6.13: Remote monitoring screen.

6.1.5 Using the GSHP to heat the engines at Markham

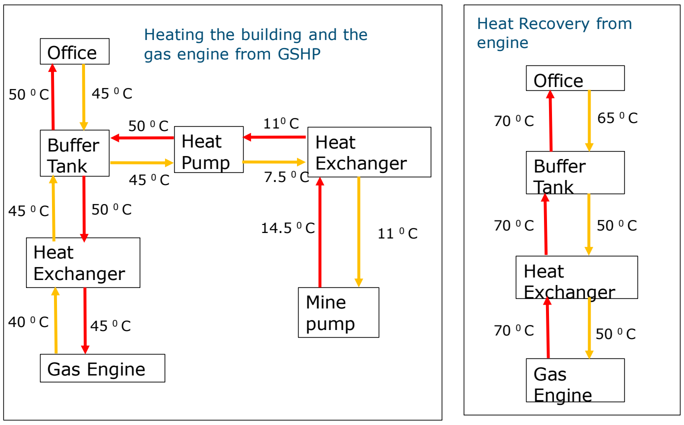


Figure 6.14: Schematic of the GSHP engine heating.

There are two natural gas engine generators at Markham that are used to generate electricity, when there is a demand for electricity from National Grid, UK. This kind of generation is known as STOR (Short Term Operating Reserve) (National Grid, 2016). The engines can be pressed into service within a short space of time, in order to do that, the engines are pre-warmed in the standby mode. An Electric heater was providing the heating. Recently the GSHP has been extended to provide heating for one of the engine as well. The other benefit is that when the engine is running, the heat from the engine is recovered and stored in the buffer tank and used for space heating, negating the use of GSHP. Using the GSHP by coupling it with a conventional system, increases the overall efficiency. This coupling of GSHP with the engine was not a part of the initial research work and was added later and no experimental work has been carried out, as the engine is run mainly in the evenings of the winter months of November to February, when the demand for the energy is the greatest and there is less day light hours and very little energy is generated by solar.

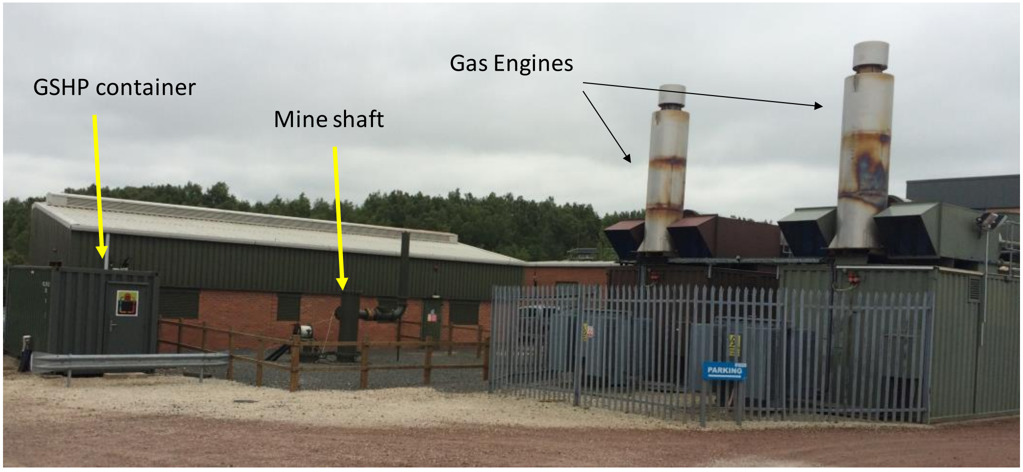
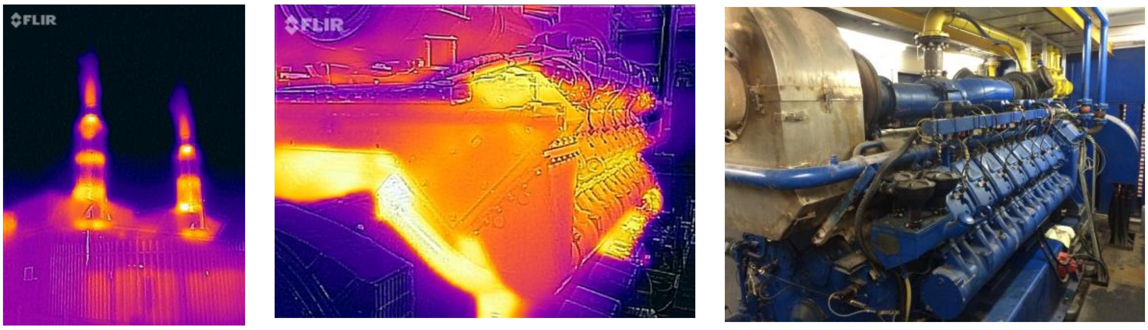


Figure 6.15: The standby gas generators at Alkane Energy, Markham.



(a) (b) (c)

Figure 6.16: (a) The thermal image of the engine in operation mode. (b) The thermal image of the engine in standby mode. (c) Normal image of the engine.

The Figure 6.15 shows the location of the engine, GSHP plant and the mineshaft. Figure 6.16 shows the thermographic image of the engine in standby mode and the amount of heated that is being ejected out through the engine exhaust when the engines are in operation.

$$COP_{system}=\frac{Q_{HP}}{W_{HP\ electrical}+W_{MP\ electrical}} \quad (32)$$

The efficiency (COP) of the GSHP system is given by the Equation 34, where Q_{HP} is the thermal energy output given by the heat pump in kJ, $Q_{HP\ electrical}$ and $W_{MP\ electrical}$ are the electrical energy consumed by the heat pump and the borehole pump respectively.

When the engines are in operation, a part of the thermal energy from the engine coolant is recovered and is stored in the buffer tank as hot water and this hot water is circulated around the office blocks to keep them warm. Thus negating the need to switch on the GSHP.

$$COP_{modified}=\frac{Q_{HP}+Q_{recovered}}{W_{HP\ electrical}+W_{MP\ electrical}} \quad (33)$$

Equation 35, gives the relation to calculate the improved COP, where $Q_{recovered}$ is the thermal energy recovered from the engine coolant and stored in the buffer tank. $COP_{modified}$ is the improved COP.

$$COP_{modified} > COP_{system} \quad (34)$$

The performance of the GSHP system along the heat recovery from the engine could not be tested and hence no results of this system has been presented in this thesis.

6.2 Caphouse pilot plant

6.2.1 The site location and geology

The National Coal Mining Museum for England (NCM, 2016) is on the site of former Caphouse Colliery, it is located in Overton, near Wakefield, Yorkshire, UK at 53.6416 ^{0} N 1.6251^0 W. Lower Coal measures in the west and the Middle Coal measures in the east underlie the Caphouse Colliery complex. The strata consist of cyclical fluvio-deltaic sequences of interbedded sandstone, siltstone, mudstones, coal and associated seatearth, the regional geology dips at an average angle of 3-5^0 in southwest direction. Caphouse Colliery complex was interconnected to other collieries in the area including the Denby Grange Colliery (53.6340 ^{0}N 1.5942 ^{0}W) and Woolley Colliery (53.5961 ^{0}N 1.5338 ^{0}W) (INWATCO, 2005a; INWATCO, 2005b). The Flockton Thick, Flockton Thin, First Brown Metal, Old Hards, Third Brown Metal, Green Lane, New Hards, Wheatley Lime/Old Man, Blocking and Beeston coal seams have been exploited at the Caphouse colliery complex (Brown, Goodchild and Collierv, 1979), (Wilcockson, 1950). The coal mines in this region of Yorkshire and Nottinghamshire has an average sulphur content of 2.13%. The Caphouse Colliery was sunk in the year 1780 (Faull, 2011) and the hope pit was opened in 1830 (Schofield, 2003; Goodchild, 1983). The Colliery complex was closed in the year 1985, the museum was opened in the year 1988, and the underground galleries were opened to public. In order to keep the underground galleries, dry and safe for the public, the water was pumped from the pit and discharged into river Calder, the pumping continued until 1993. The pumping of water of the resumed in the year 1996, when the water level started to rise due to a loss of hydraulic connectivity (perhaps due to a collapse of a road way) with neighbouring Woolley shaft (Faull, 2011).

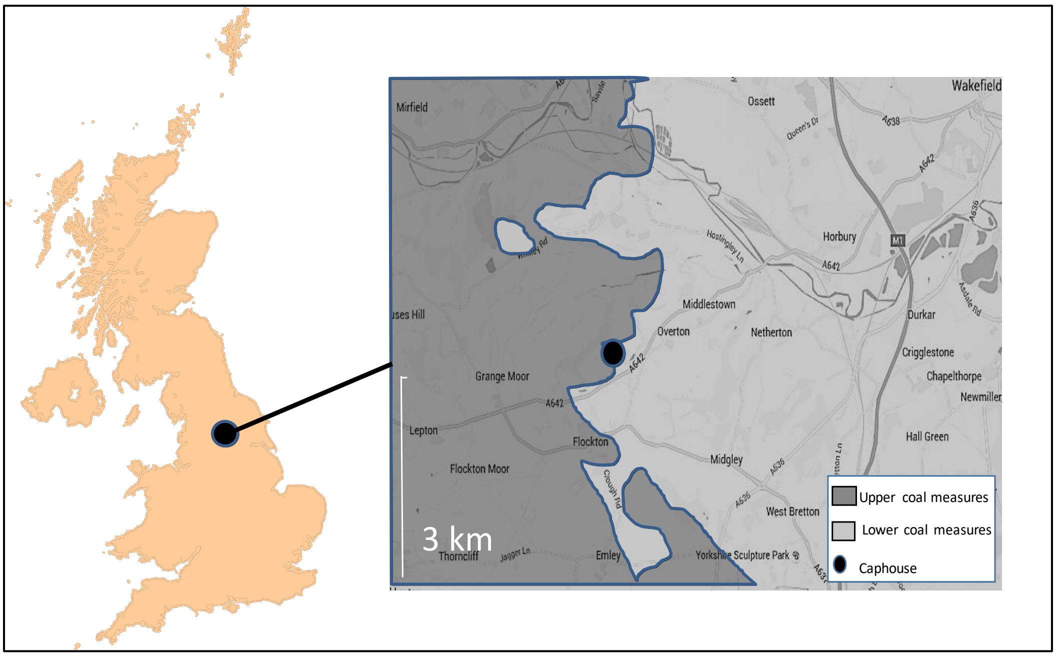


Figure 6.17: Location and the coal measure geology of the site.

6.2.2 Mine water dewatering and treatment system

As mentioned earlier, in order to keep the underground galleries of the museum dry and safe for the visiting public, the dewatering pumps are used to pump out the water at a flow rate of circa 30 l/s from the shaft and is discharged into the Calder river. The temperature of the water pumped varies from 11^{0}C in winter to 15^{0}C in summer. Mine water has an iron content of circa 15 mg/l and is partially oxidised in the pumping shaft and hence precipitation of ochre takes places (Burnside, Banks and Boyce, 2016). To prevent contamination of the river water downstream, the water undergoes passive treatment using several settling tanks and reed beds to remove the ochre before discharging it into a water stream. Figure: 6.18 presents a Google satellite image of the water treatment tanks where the orange colour due to ochre is clearly visible.

Figure: 6.18: Google map image of the water treatment facility

6.2.3 Pilot plant description

The schematic of the system is as shown in the Figure 6.19. The GSHP system consists of a single 10.5 kW commercial Vaillant heat pump, two sets of prophylactic shell and tube type heat exchangers. Only one heat exchanger is used for operation and the other one is always kept on standby. A mesh filter is also used to provide initial filtration before the heat pump. The filter unit also includes two separate filter baskets that can be easily swapped by turning the knob, to allow for maintenance, similar to the heat exchangers. A 300 litres buffer tank is used to allow stable operation of the heat pump during fluctuation in heating demands. The heat from the system is used for heating the old Inman shaft building that is currently used as an exhibition space at the museum. In order to keep the mining museum galleries dry, water needs to be pumped daily, at a flow rate of circa 30 l/s. During the winter months, water is pumped 24 hours a day and in summer months, the water is pumped for circa 15 hours a day. A small amount of mine water is tapped from the main pumping header line and used in the pilot plant and later injected back to mine water treatment lagoon. Figure 6.20 presents a satellite image of the location and a schematic diagram of the pilot plant system. Figure 6.21 presents further details about the components of the system, where Figure 6.21-a presents the Inman building, Figure 6.21-b presents the first lagoon where the water from the coal mine is first discharged to, Figure 6.21-c presents the location of the container that includes the system and Figure 6.21-d presents part of the container and the two main header pipes through which mine water is pumped to the treatment lagoons.

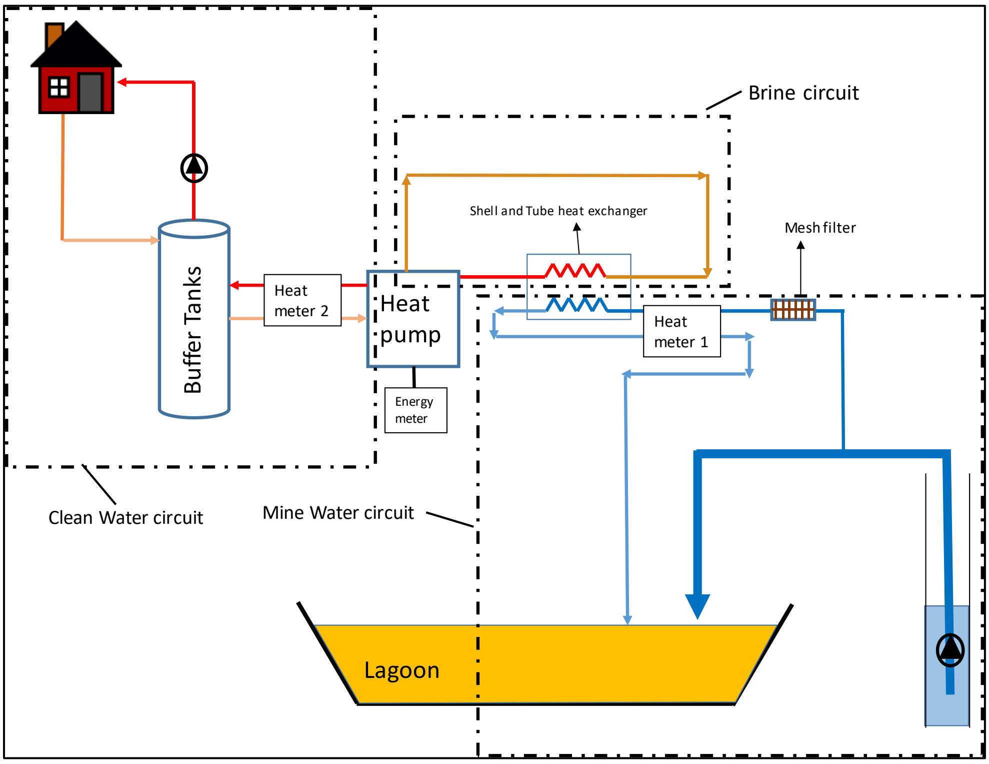


Figure 6.19: The schematic of the pilot plant at NCM.

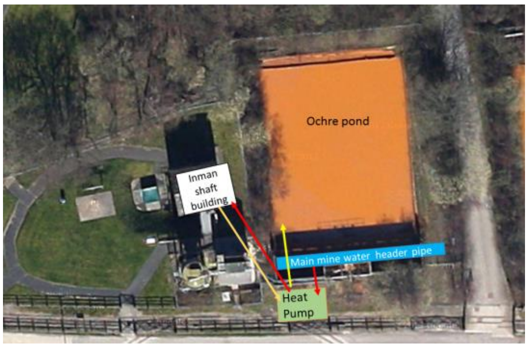


Figure 6.20: The satellite image of the GSHP system

Figure 6.21: (a) Inman shaft building. (b) Mine water treatment pond. (d) GSHP system container. (d) Main mine water discharge header pipes

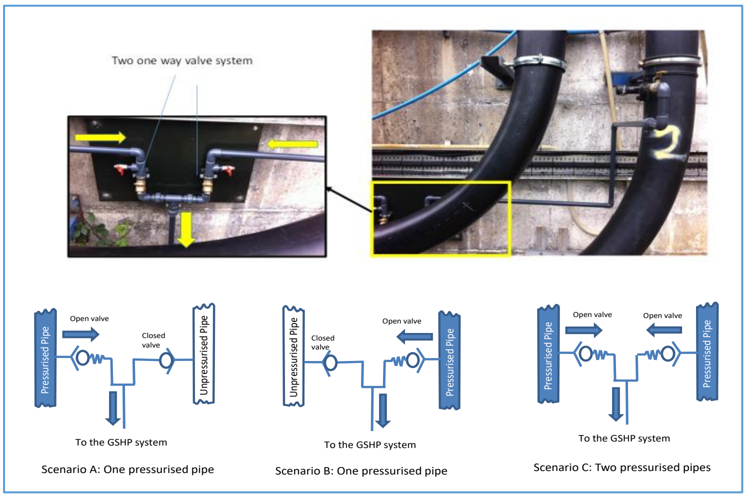


Figure 6.22: Mine water extraction for the pilot plant from main header line

The system for pumping water from the coal mine includes two parallel systems (header pipes) one or both could be operating at any specific time. To allow the extraction of water by either pipe, a novel design (see Figure 6.22) allows the heating system to circulate water from either pipe based on their pressure, and at the same time preventing the loss of pressure due to water leakage to the low pressure/empty one. If both systems are pressurised, this will create a functional flow based on the lowest pressure assuming both are above the threshold value of the valves.

Figure 6.23 : (a). Vaillant GSHP unit. (b) GSHP display screen

Figure 6.24: Buffer Tank. (b) Prophylactic Shell and Tube Heat Exchanger. (c) Duplex Filter

6.2.4 Data Acquisition and Monitoring of the system

The main parameters that need to be monitored to determine the performance of the system are energy consumption and heat transfer rates between mine water and the brine. These are determined by measuring the fluid input and output temperatures and instantaneous flow rates. Two Multical 602 Kamstraup heat meters are used to monitor both mine water and heat pump output parameters. The heat meter measures the flow rate in m^3/h, ΔT of water in degree C, instantaneous power in kW and cumulative energy in MWh. The Multical 602 Kamstraup heat meter consists of an integrated flow and temperature sensors and an integrator to calculate the energy based on the flow and temperature values. The entire monitoring system is coupled to telemetry and the data is continuously collected. The electricity consumption is measured using an 'Autometer 100m' energy meter.

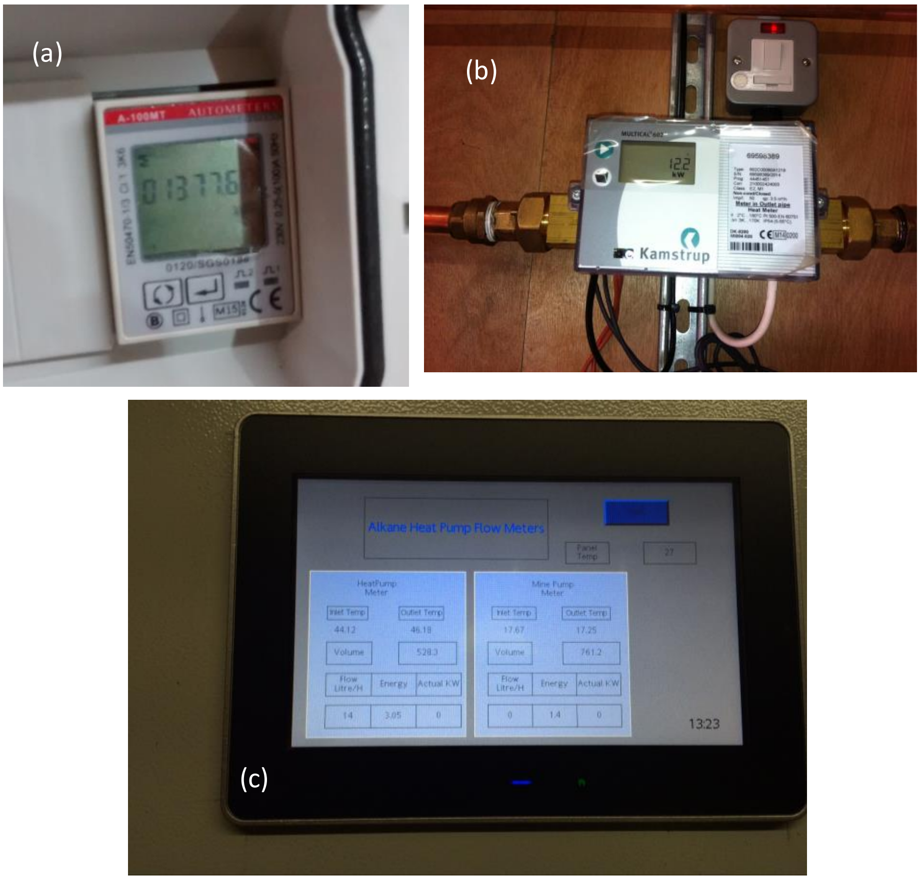


Figure 6.25: (a) Energy meter. (b) Heat meter. (c) Data acquisition unit.

7 Results and discussions from the field trials

The results of the field trials of the heat pump at Markham and Caphouse has been presented in this chapter. The main parameters affecting the COP of the heat pump are the water flow rate, differential temperature, electricity input and hot water output. Since the heat from the heat pump was being used to heat the office blocks, there was very little leverage available to change the hot water output temperature, as the office and the storeroom could not go below a certain temperature, as this could have adverse impact on the people working in the office and on the components kept in the storage depot.

7.1 Markham

At Markham, water from an abandoned flooded mine shaft is pumped and after extracting energy from it, the water discharged back into the same shaft. GSHP upgrades this energy and is used to heat the buildings on site. Further details about the Markham site and experimental set up has been described in detail in the previous chapter. The brief description of the experimental run is as follows:

- The heat was being provided to the office block using the GSHP and it used three different types of emitters (Underfloor heating, fan coil unit and oversized radiators).
- An inverter was connected to the borehole pump to reduce the electricity consumption of the borehole pump.

- Mine water does not directly pass through the GSHP, but instead passes through a shell and tube heat exchanger, where brine extracts the energy from mine water and transfers it to the GSHP.
- Hot water from the GSHP is pumped into a buffer tank and from the buffer tank, the hot water is circulated around the buildings.
- The system is connected to telemetry system. The container electricity consumption, heat pump electricity consumption, mine pump energy consumption and mine water energy data were recorded.
- The borehole pump is installed at a depth of 170 m below ground level and return hose is at a depth of 153 m below the surface.

7.1.1 Operations

The performance of the GSHP system operations during the field trials is presented here. During this period, the average efficiency (COP) of the heat pump was 3.59 and the overall efficiency of the whole system was 1.59. A number of dynamic factors including outside ambient temperature, inside room temperature, heat pump outlet hot water temperature, temperature of mine water being extracted, affects the efficiency. The power consumed by the borehole pump has a big impact on the overall system efficiency, if the heat pump efficiency is considered relatively constant.

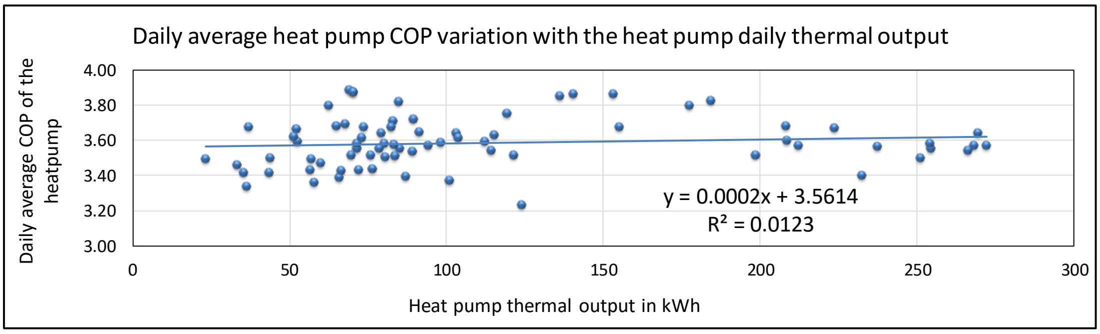


Figure 7.1: The relation between heat pump COP and total thermal output of the heat pump.

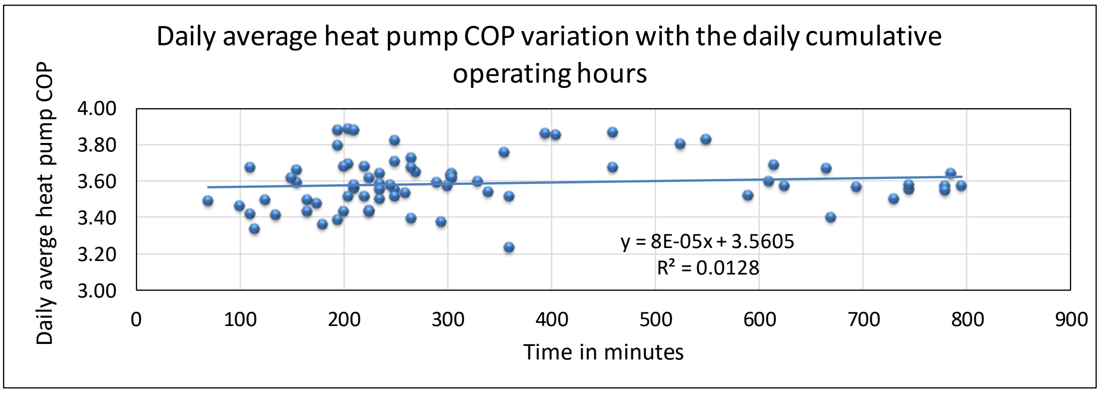


Figure 7.2: The Heat pump COP for different hours of operations.

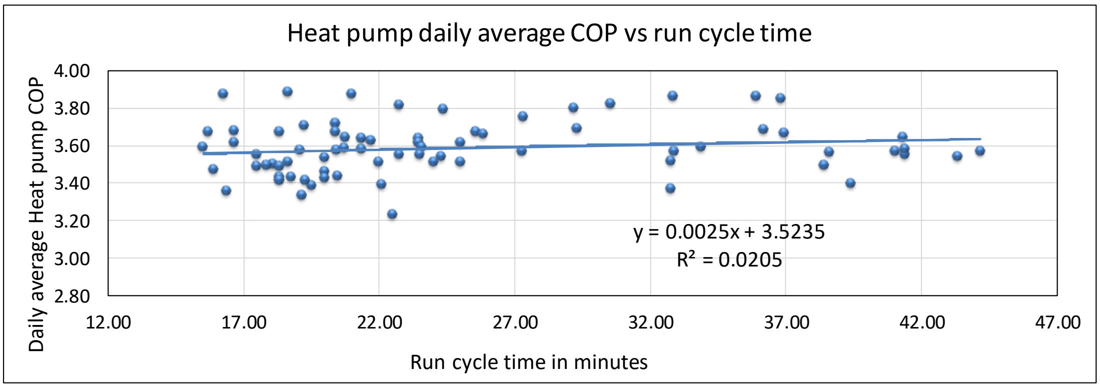


Figure 7.3: The relation between heat pump COP and duration of each run.

The Figure 7.1, Figure 7.2 and Figure 7.3 show that the COP of the heat pump is circa 3.6 and trend line is almost parallel to the X-axis. From Figure 7.4, it is visible that, as the heat pump runs between 22 to 27 minutes in each cycle, the COP is higher and the range of the variation is low. When the cycle time is less than 22 minutes the COP is lower and the range of variation is high. The lower values of COP of the heat pump must be attributed to the lower heat demand from the building, as the GSHP would have running at sub optimal operating condition resulting in cycling of the compressor of the heat pump.

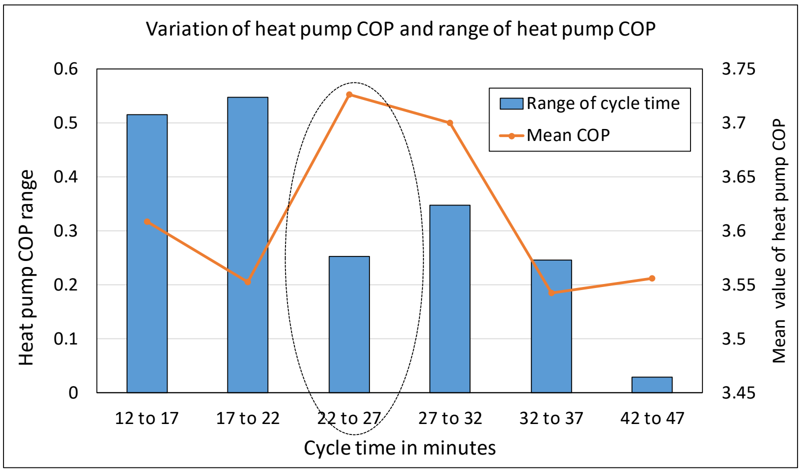


Figure 7.4: Variation of COP and range of COP of heat pump.

The temperature of the incoming mine water has remained stable during the operation. Figure 8.5 and Figure 8.6 indicate that there are no big variations in the incoming mine water temperature over time, mine water energy is constantly replenished by the geothermal rocks and fresh inflow of warm water into the mineshaft from other coal seams. Mine water in the abandoned coal mines therefore represents a huge reservoir of low enthalpy water that is a reliable source of energy that can be used profitably used for heating applications over a long time without fearing for any loss in its energy content.

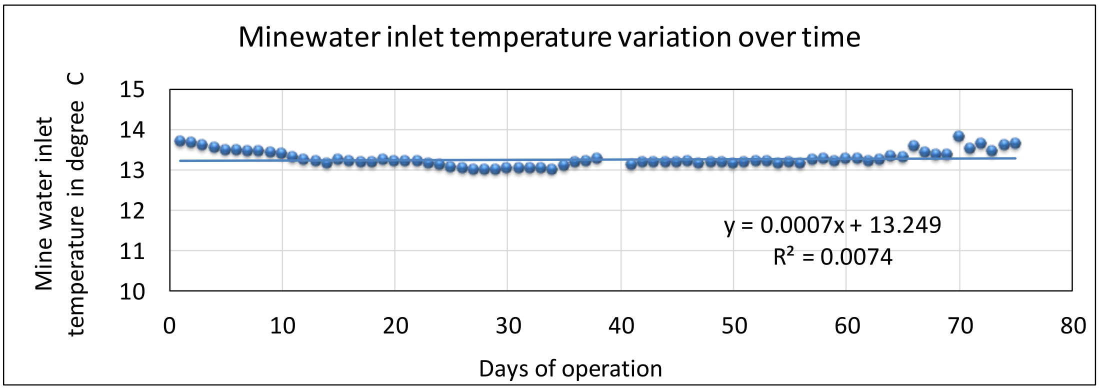


Figure 7.5: Mine water inlet temperature fluctuations over time.

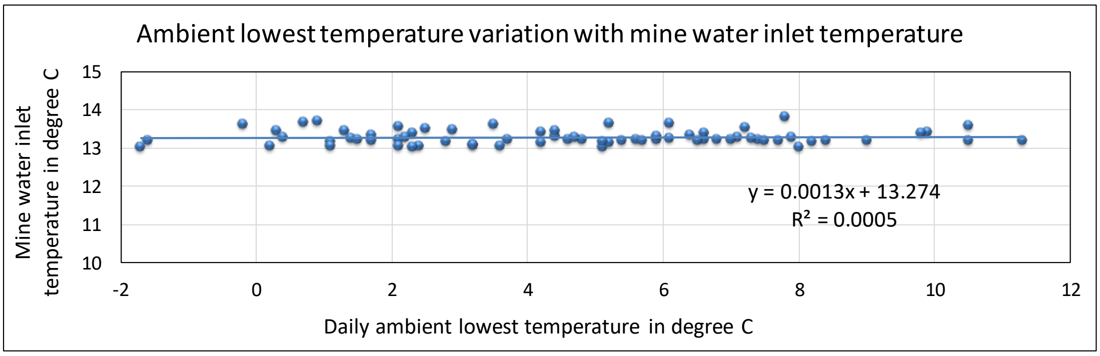


Figure 7.6: Mine water inlet temperature variation corresponding to the volume of mine water utilised in a day.

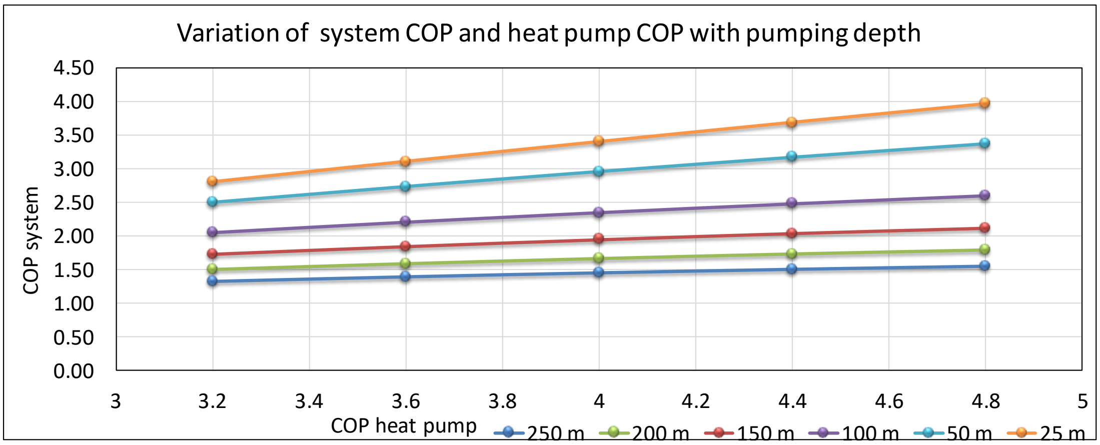


Figure 7.7: The relationship between the depth of water in the coal mine, COP of the heat pump and COP of the system.

Figure 7.7 presents the relationship between the depth of water in Markham and its relationship with the COP values of heat pump and the COP of the whole system. At the depth of 100 meters, the overall COP value is about 2.7

when the COP of the heat pump is 4.8. This means for every 1 kWh consumed by the system, 2.7 KWh is produced as an output. The difference in energy is the energy extracted from the water in the mine. The water will sustain regulated temperature due to the geothermal energy and the significant volume of water in the coal mine. Due to the rising water level in the shaft, the overall COP is expected to reach a value of approximately of 3.97 at a depth of 25 meters, with the heat pump COP reaching 4.8.

7.1.2 Carbon emissions

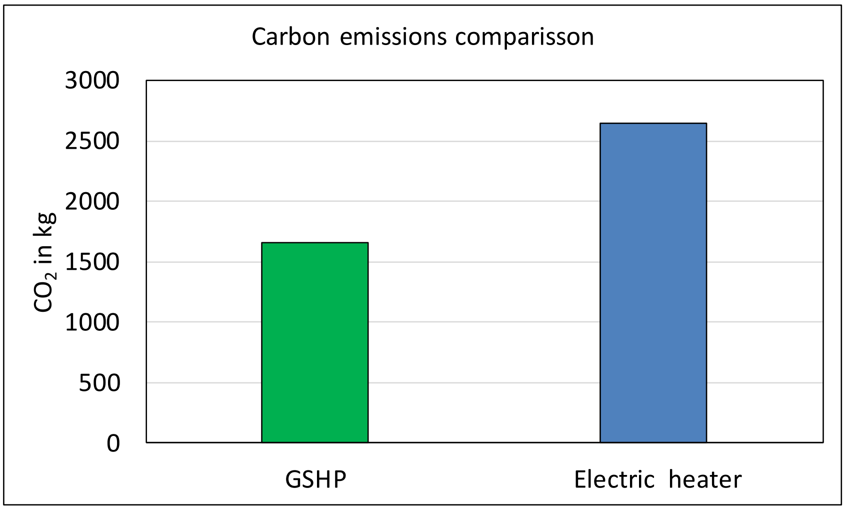


Figure 7.8: Carbon emission comparisson from the field trials.

The UK grid electricity has a carbon emission factor of 0.5331 kg/kWh (DECC, 2015). The carbon emission for the GSHP system was 1663.38 kg, if an electric heater was used instead of GSHP the carbon emission would have been 2645.5 kg. By using GSHP, the carbon emission has reduced by 37 %.

7.1.3 Operating costs

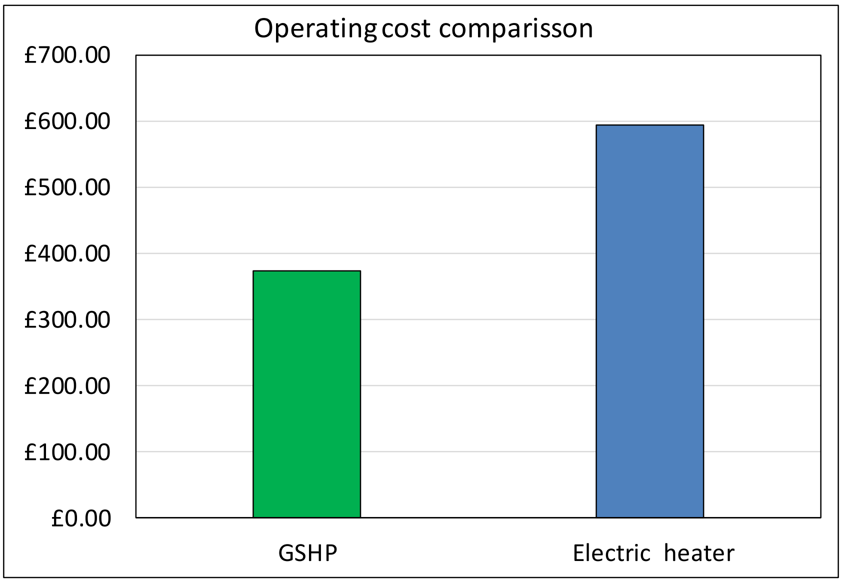


Figure 7.9: Operating cost comparisson from the field trials.

Considering an electricity price of £0.12/kWh, the operating cost of using GSHP to heat the office buildings is £374. It would have cost £595. If an electric heater was employed to heat the office building. Therefore, the use of GSHP has reduced the operating costs by 37 %.

7.2 Caphouse

At Caphouse, the water is being pumped from the shaft and discharged to a stream after treating the water to remove the ochre by passive treatment method. The water is being pumped at circa 30 l/s. the water is pumped 24 hours a day in winter and circa 15 hours in summer. As the water being pumped already no additional power is used, hence the overall COP of system will be equal to the COP of the GSHP.

The GSHP plant design at Caphouse is similar to that of Markham. The details of the system are as follows:

The temperature of the incoming mine water was always constant at circa 15 ^{0}C.

Mine water was already partially oxygenated in the shaft due to this there ochre accretion, which was accumulating in the filter basket and blocking the flow.

7.2.1 Operations

Since the water was already being pumped out no pumping costs are involved. The average COP of the heat pump was 4.28. The performance and COP of the heat pump was slightly more than expected value of 4. Further details about the performance is given below.

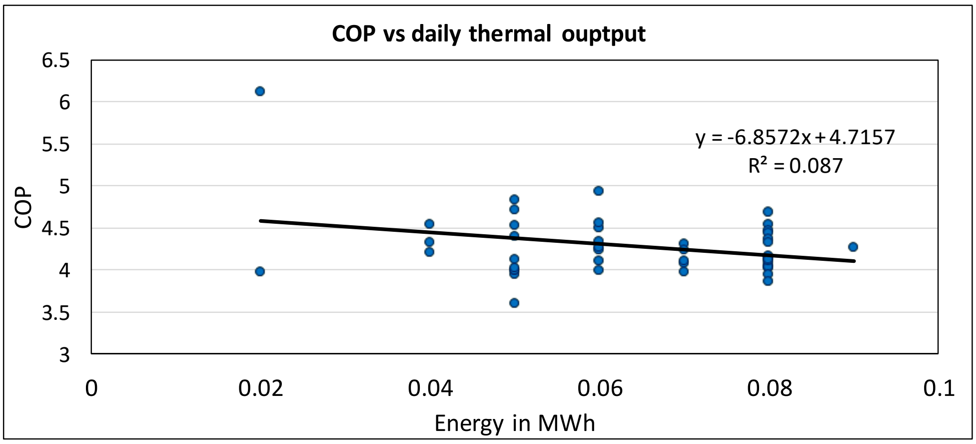


Figure 7.10: Daily average COP vs the total thermal output from the heat pump.

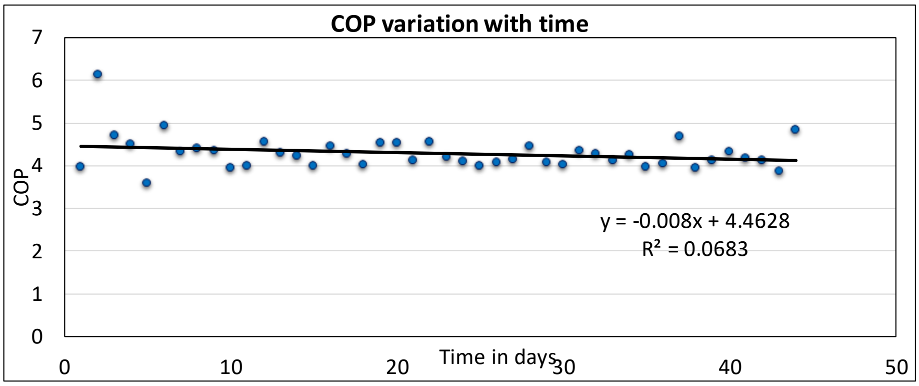


Figure 7.11: COP variation over time.

The daily average COP does not seem to vary much due to any changes in the heating needs of the building and the COP has been 4 and above for most of the run, touching 5 on few occasions.

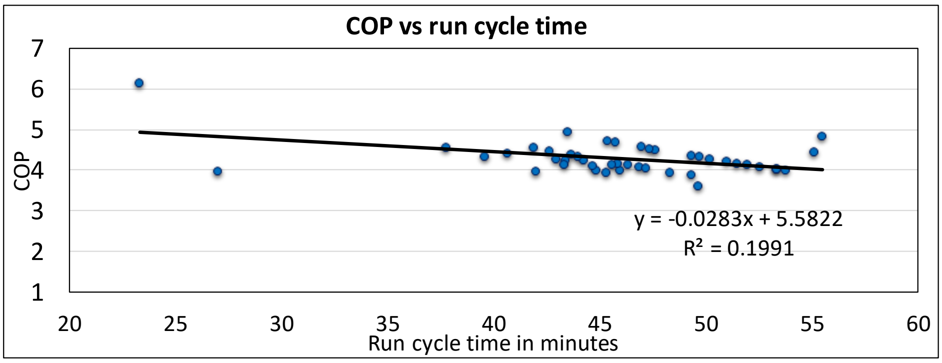


Figure 7.12: COP vs run cycle time.

The heat pump has run for at least for 40 minutes in each of the run for most of the time. The overall average daily COP of the heat pump has been more than 4 for most of the time. There does not seem to be any instance of cycling.

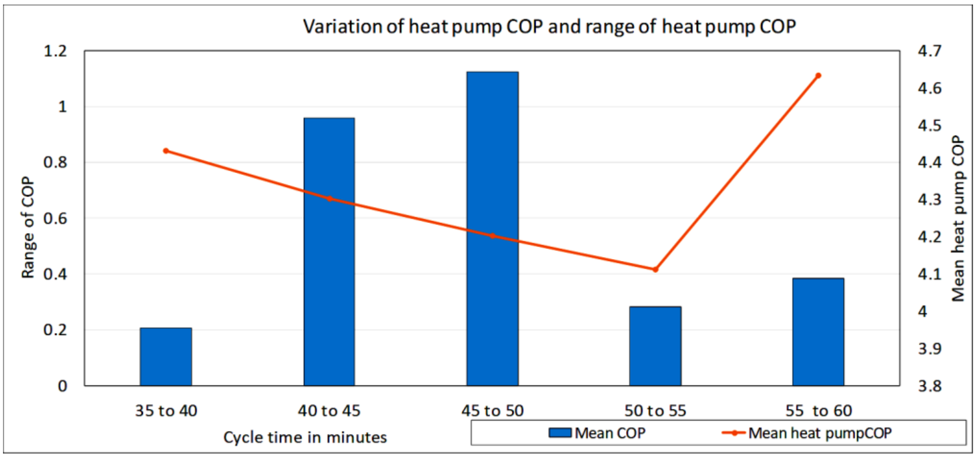


Figure 7.13: Variation of COP and range of COP of heat pump.

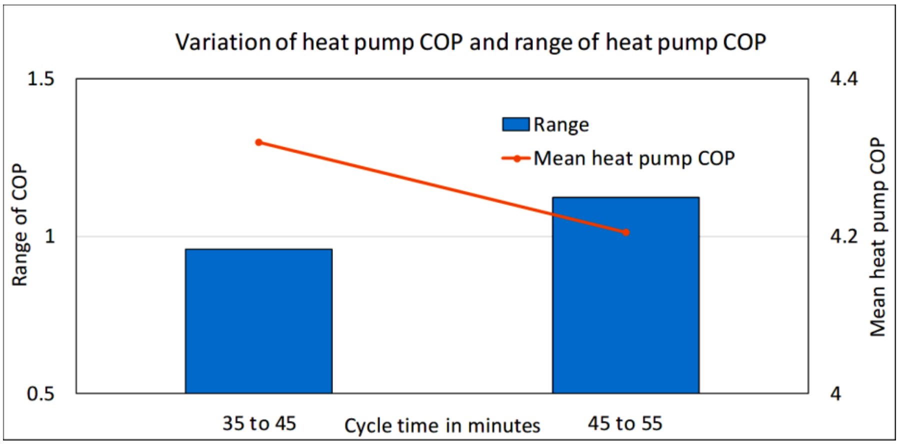


Figure 7.14: Variation of COP and range of COP of heat pump.

Figure 7.13 shows the variation of range of COP and mean COP of the heat pump. Most of the data are between 40 to 50 minutes range and not much data points are available outside this range, hence in Figure 7.14 the data has been consolidated into 35 to 45 minutes and 45 to 55 minutes to get a more accurate picture. The COP value is 4.3 in the former case and 4.2 in the latter case. The variation in range and COP value is fairly consistent.

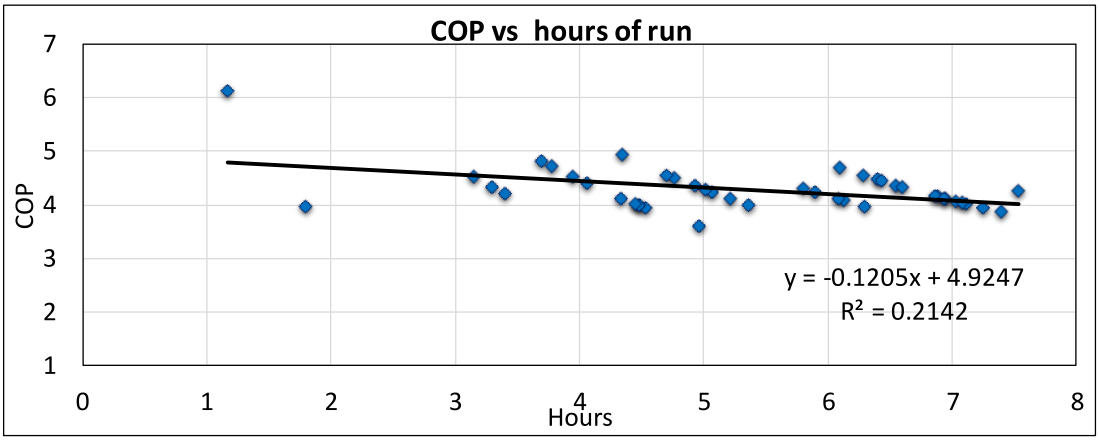


Figure 7.15: COP variation vs the total operating hours in a day.

The overall average daily COP has been above 4 for most of the time. There does not seem to be much change in the performance of the heat pump due to the change in operating hours

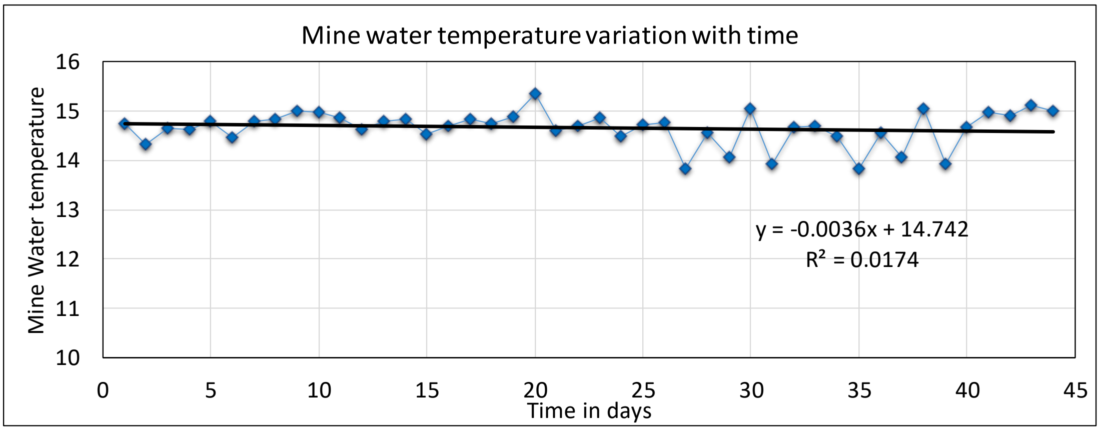


Figure 7.16: Mine water inlet temperature variation with time.

From Figure 7.16, it can be seen that the temperature of mine water does not vary much over time and hence removes any threat of any reduction in water temperature and reduced COP.

7.2.2 Operating cost

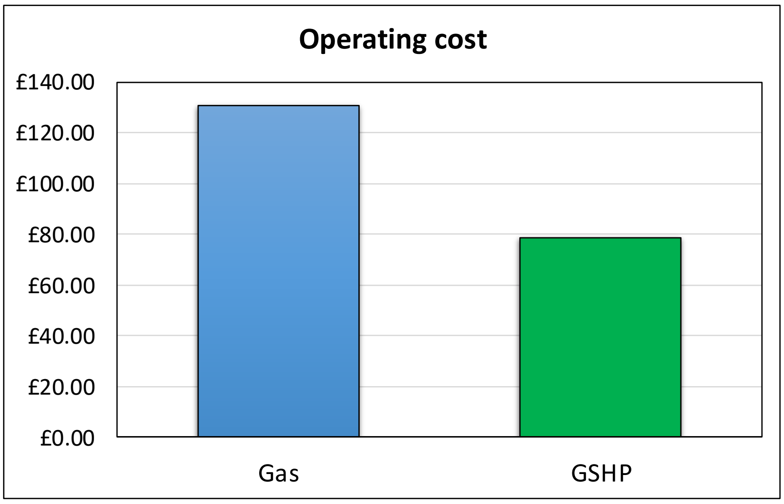


Figure 7.17: Operating cost comparisson from the field trials.

Considering an electricity price of £0.12/kWh, the operating cost of using GSHP to heat the Inman shaft building is £78.8, it would have cost £130.8, if a gas boiler was employed to heat the building. Therefore, the use of GSHP has reduced the operating costs by 41.8 %.

7.2.3 Carbon emissions

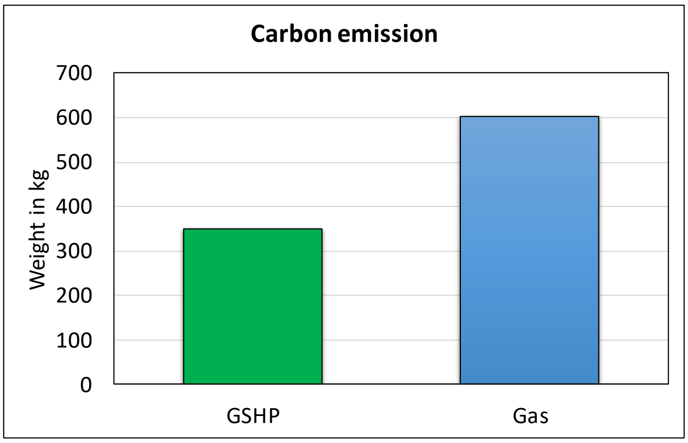


Figure 7.18: Carbon emission comparisson from the field trials.

The UK grid electricity has a carbon emission factor of 0.5331 kg/kWh and the gas has an emission factor of 0.184 kg/kWh (DECC, 2015). The carbon emission for the GSHP system was 350 kg, if a gas boiler was used instead of GSHP the carbon emission would have been 601 kg. By using the GSHP, the carbon emission has reduced by 41%.

7.3 Ochre accumulation

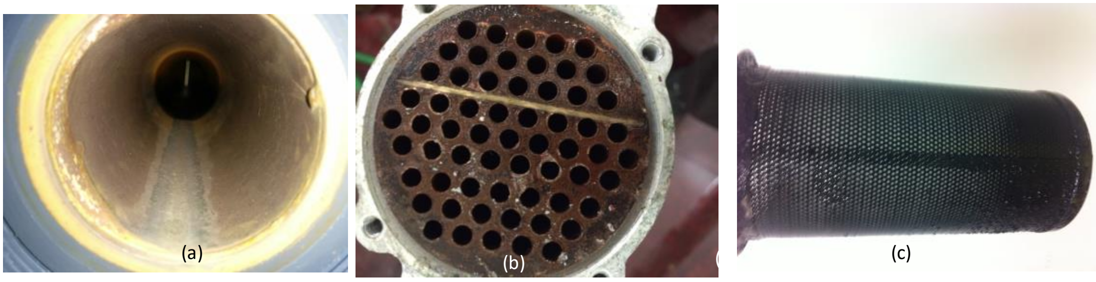


Figure 7.19: (a) The pipeline. (b) Heat exchanger. (c) Filter.

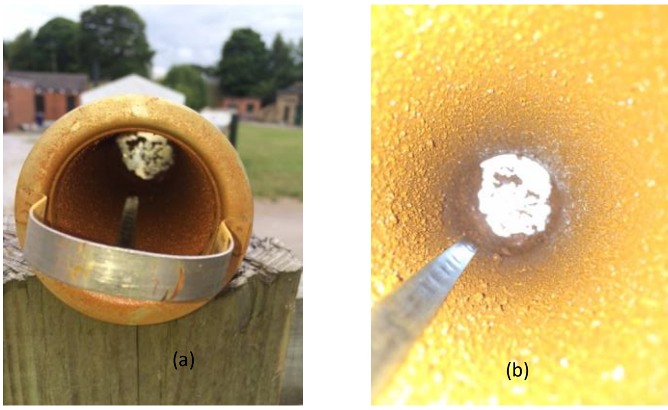


Figure 7.20: Ochre accumulation in the filter.

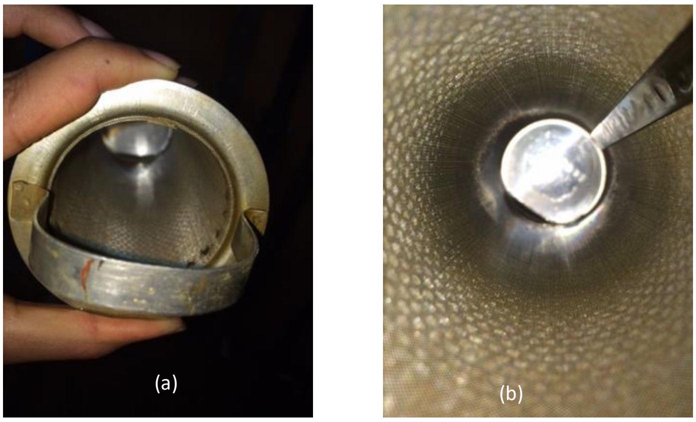


Figure 7.21: Clean filter.

Figure 7.19, shows the condition of the pipeline, heat exchanger and the filter at the Markham site. It can be seen that there are no issues of clogging due to mine water. Figure 7.20 and Figure 7.21 show the filter condition before and after the GSHP run at Caphouse, there is accumulation of ochre at Caphouse. The reason for the accumulation of the ochre at Caphouse and no accumulation at Markham is because the raw mine water is exposed to oxygen at Caphouse, whereas at Markham, due to the design, the oxygen is prevented from coming in contact with the raw mine water and prevents the formation and accumulation of ochre.

7.4 Comparison between Markham and Caphouse system performance

When the two open loop systems at Markham and Caphouse are considered, the performance of the heat pump at Caphouse is better. This is because of the following reasons:

- The buffer tank capacity at Caphouse is twice as big as that of Markham's, when considered with per capita heating capacity of the heat pump. It takes 10 minutes to completely heat up the buffer tank at Markham and it takes 20 minutes to heat up the buffer tank at Caphouse. This has eliminated the cycling of the compressor of the heat pump, hence better efficiency.
- The differential temperature of the inflow and return of mine water ΔT is circa 5.1^{0}C at Caphouse, where as it is circa 2.28^{0}C at Markham. Therefore, less energy is being harnessed from mine water at Markham and the heat pump is having to work hard
- The average run per cycle of the GSHP at Markham is 24.99 minutes and at Caphouse is 45.96 minutes.

7.5 Summary

This chapter has described the performance details of the two pilot plants. The design employed to harness energy from mine water through a GSHP has produced higher efficiencies and has been effective in cutting the operating costs and carbon emissions. The design has been found to be effective in eliminating the ochre formation and hence clogging at Markham and at Cahouse, where the ochre is already formed in the shaft, the prophylactic heat exchanger and the filter ensure that the plant runs without any stoppage and with minimum maintenance. The GSHP is very effective when it replaces the electric heater in reducing the operating costs compared to a Gas boiler

8 Conclusion

The main aim of this research work is to investigate the feasibility of using mine water along with a heat pump as a reliable, economical and environment friendly low carbon energy resource and take a novel theoretical concept into commercial deployment stage. A tool is developed to assist in the design of mine water heating system using a theoretical approach and theoretical case studies are conducted for three sites. Experimental work is also conducted to study the performance in field and get the actual data from the field, as not much information is currently available. The details of the methodology, case studies and results from the field trails are discussed here. The thesis ends with the key findings and a section on further work that can be done in this field.

8.1 Fulfilment of the objectives

To fulfil the above aim of taking a theoretical concept of harnessing the energy from mine waters and using it for space heating, to a commercial deployment stage, the objectives defined in chapter 1 are met as follows:

- Literature survey is carried out to understand the theoretical concepts and the previous work that had been done in this field. The following key characters were identified:
    - The temperature of mine water, flow rate, the differential temperature ΔT between the flow and return of mine water, depth of the water from the surface (if the water is to be pumped) and

water quality are the main parameters which need to be considered.

- The depth of mine water level from the surface has a huge impact on the overall efficiency of the system. There are many former colliery sites where water is still being pumped out and these sites are ideal for the installation, as most of the pumping infrastructure is already in place.
- Even if the water has to be pumped from an existing mine shaft or a borehole, eventually water will rise close to the surface and less pumping power will be needed. Thereby increasing the efficiency and financial savings due the reduction in the operating cost.
- Performance of a heat pump (COP) is mainly dependent on the temperature of mine water coming out of the mine and hot water temperate going into the building. COP is directly proportional to the temperature, higher the temperature of mine water greater will COP. COP is inversely proportional to the hot water temperature going into the building.

- A theoretical analysis is carried and a generic design tool is developed to assist in the design process. The tool considered the technical, financial and environmental aspects. The tool is helpful in making a quick decision on whether the project is feasible to go ahead further to a detailed design stage.
- Case studies are conducted for three sites with different site conditions.

- Pilot plants are built at Markham and at Caphouse and field trials were conducted to test the system experimentally as well.

8.2 Reflection on the methodology

The main aim involved taking a theoretical concept into commercial launch stage. For this, the methodology involved conducting literature survey, theoretical case studies and testing the concept by building the pilot plants and conducting field trials.

In the literature survey, key parameters are identified for the theoretical analysis and a design tool is developed. The tool developed offers a quick method to evaluate the feasibility of the project. It uses a step by step approach to size all the components of the heat pump and calculate the financial and environmental benefits. Based on the peak thermal power demand, the size of the heat pump is determined and if required, based on the pumping depth, the borehole pump size required is calculated. All other accessories that are needed including the buffer tank and heat exchangers are sized up. The financial aspects including calculating the operating costs, savings in comparison with a conventional system and the potential income that can be obtained from the RHI scheme. The environmental benefits include, calculating the reduction in carbon emissions in comparison with a conventional heating equipment.

Pilot plants are built at two sites (Markham and Caphouse) with different site configurations. This was mainly to check what negative impact mine water had on the maintenance requirement. The maintenance issues regarding the clogging was identified initially and design had taken into consideration the need to frequently clean the filter and heat exchanger. Hence, a standby prophylactic heat exchanger and a filter is also installed to run the system continuously with minimum stoppage time.

8.3 Feasibility of the case studies

The case studies are conducted for three different sites, one where mine water is already being pumped and is being discharged into a river after removing all the impurities, second site involved pumping the water from an existing mines shaft where the water had already recovered. Third site involved pumping water from a deeper shaft and discharging the water back to the same shaft, but with a steadily rising water level. Technically it showed that is possible to build and run a mine water based heating system successfully, which is also financially viable depending on the site status. Results of the case studies show that, from Figure 8.1 and Figure 8.2 it can be seen that the operating costs and the carbon emissions are significantly less when compared to the conventional heating systems like electric heater and gas boiler. The benefits of GSHP becomes more attractive when compared with electric heater than the gas boiler, due to the higher costs of electricity than the gas. The main disadvantage is the high initial capital costs needed. The system becomes economically feasible with a reasonable payback period only when it receives RHI income; see Figure 8.3. If for any reason, the government decides to remove the RHI benefits in the future, then the project becomes unfeasible, this is the only risk that can be foreseen to the project. However, for some organisations, which are mainly concerned with the environmental benefits, removal of RHI should not matter.

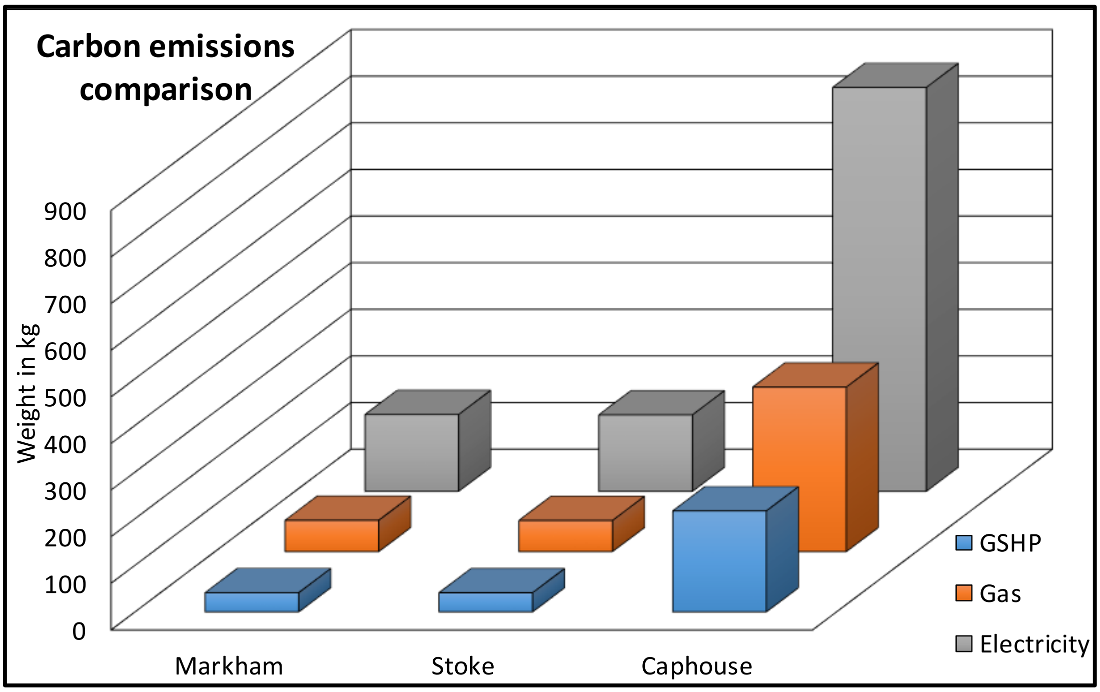


Figure 8.1: Combined carbon emission comparison of the case study sites.

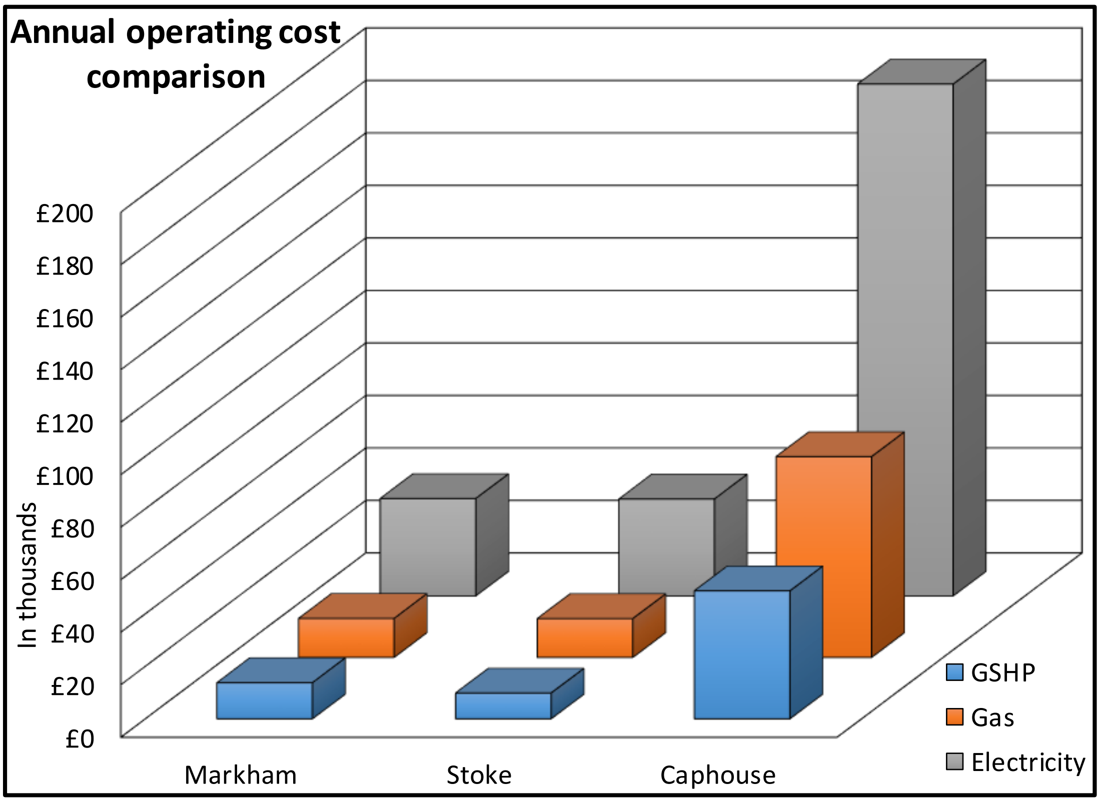


Figure 8.2: Combined annual operating cost comparison of the case study sites.

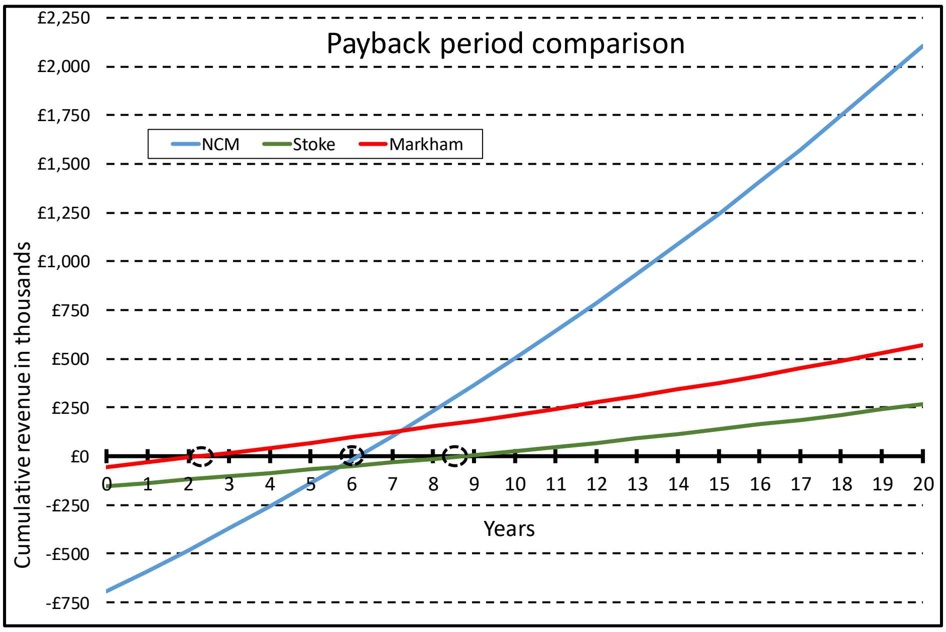


Figure 8.3: Payback period (RHI payments included) of the case study sites.

8.4 Pilot plant and Field trials

Using a site with an existing borehole or mineshaft is ideal, it is easy to get Environment Agency (EA) permits, required to pump and discharge mine water and the availability of the water is also well known. The Markham site has an existing shaft that is flooded with the water level steadily rising. The overall COP of the system is less, as considerable amount of energy is spent in pumping the water to the surface. Greater the depth of water in the shaft/borehole, greater will be the costs of pumping water and thus lesser will be the overall COP. Since the GSHP was competing with electric heater, still significant savings could be achieved. The GSHP is found to be slightly oversized and efficiency is found to be slightly less (circa 3.5) than that of the Caphouse plant due to the cycling of the compressor. No maintenance problems due to clogging issues is noticed, the filter and the heat exchangers were all in a clean condition.

At Caphouse, where mine water is already being pumped to the surface, no additional costs are required to pump the water and the COP of the heat pump is almost equal to the COP of the system. Here the efficiency of the GSHP is better than anticipated (COP more than 4). Since the GSHP was competing with gas boiler, higher COP helped to achieve significant savings in energy and operating costs. However, since the water was already oxygenated in the pumping shaft, the ochre clogging is noticed. However, filter was effective in filtering out the ochre preventing any problems further in the system or a stoppage in operations due to maintenance.

The main issue of using mine water is the potential of clogging the ochre in mine water that can cause to the equipment as noticed at Caphouse. By preventing the air from coming in contact with mine water, the formation of the ochre can be completely eliminated. The field trial at Markham highlighted this very clearly. Therefore while designing, care has to be taken to prevent mine water from coming in contact with air. See Figure 8.4.

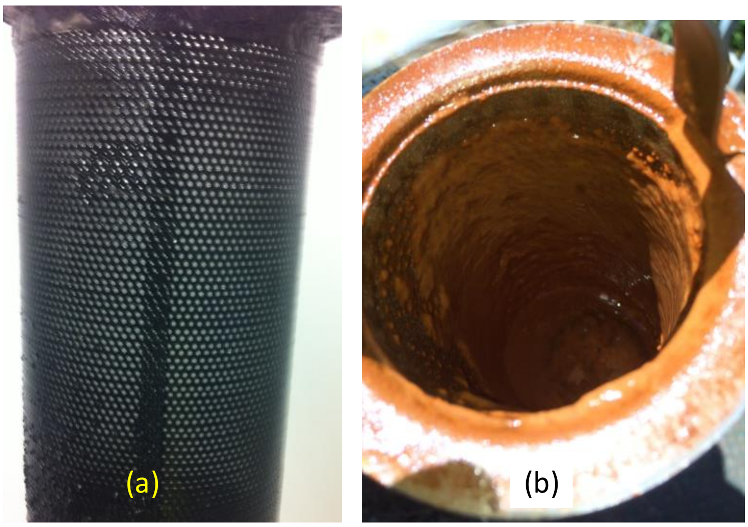


Figure 8.4: (a) Filter at Markham (clean). (b) Filter at Caphouse (ochre accumulation).

If the water in the mineshaft is already oxygenated, as it is at Caphouse, the use of prophylactic heat exchangers minimises the maintenance issue due to ochre clogging. By passing brine through the prophylactic heat exchangers (one on standby, so that if the heat exchanger were to get clogged, mine water flow can be diverted to the standby heat exchanger, while the clogged one is being cleaned) to extract heat from mine water, any potential problems of ochre clogging will be isolated and restricted only to the heat exchangers, thereby the heat pump will remain unaffected. Having a duplex filter in mine water circuit before the heat exchanger further protects the heat exchanger from ochre clogging. By having a system consisting of prophylactic heat exchangers and duplex filter, a continuous operation of the system can be guaranteed in even in an ochre rich mine water, as very little time is required to clean them.

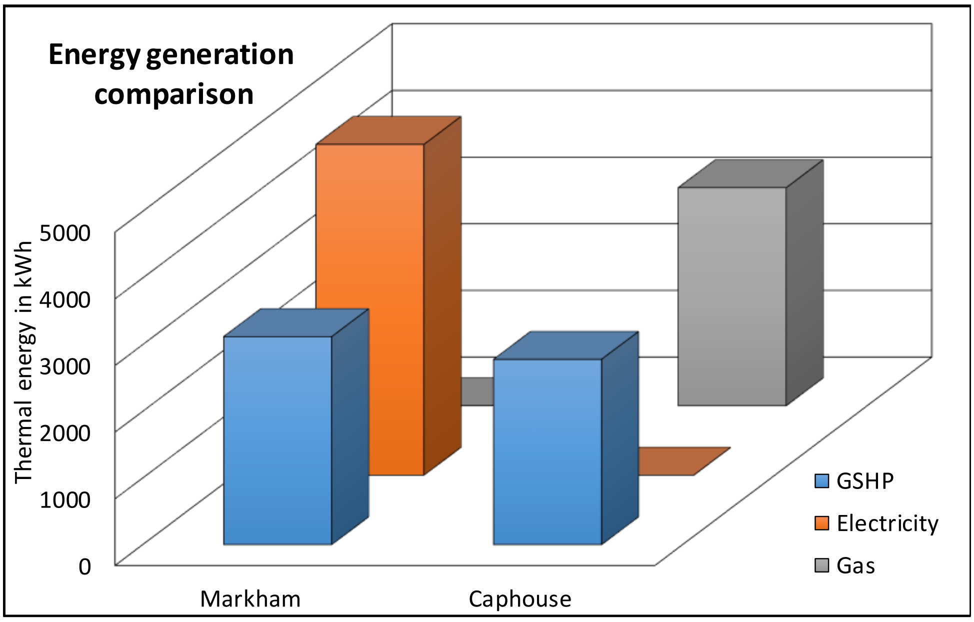


Figure 8.5: Energy generation comparison of the pilot plants.

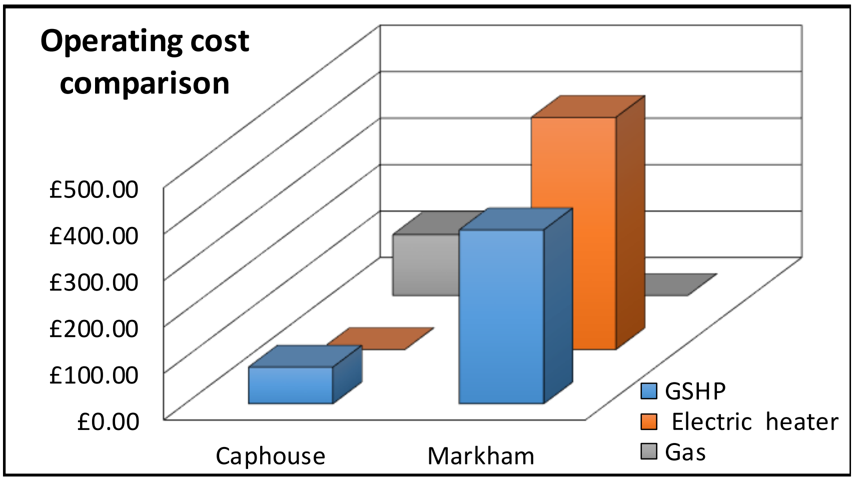


Figure 8.6: Operating cost comparison of the pilot plants.

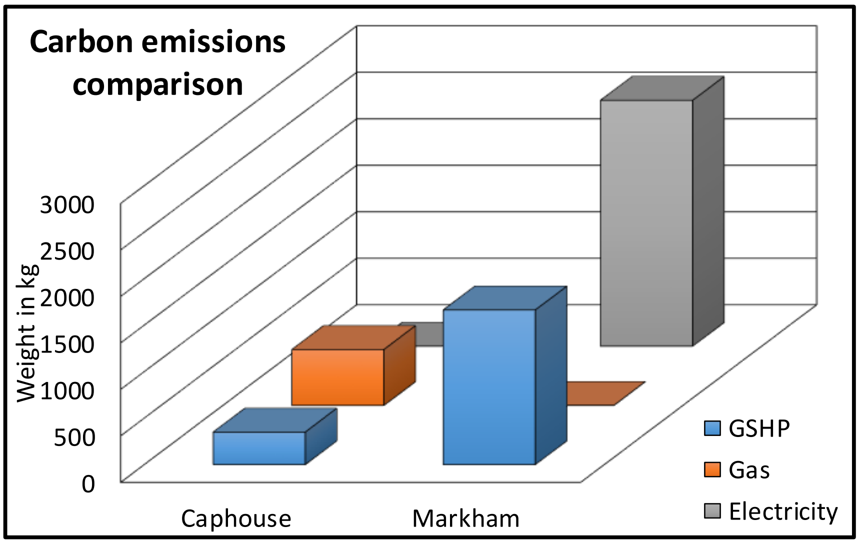


Figure 8.7: Carbon emission comparison of the pilot plants.

The field trials have clearly shown that a COP of more than 3.5 can be easily obtained and the performance is reliable for long term operations. It can be seen from Figure 8.5, Figure 8.6 and Figure 8.7, that the energy requirements of the pilot plant sites can be significantly reduced and hence the operating costs and carbon emissions are also reduced. It also showed that it is imperative to size the heat pump and other accessories appropriately to the peak thermal demand to achieve the maximum COP.

8.5 Contributions to knowledge

8.5.1 Conceptual contribution

- The thesis has investigated the feasibility of extracting energy from the flooded coal mines and has shown a sustainable low carbon way forward to many of the former coal mining towns still recovering the mine closures.
- A novel concept has been taken from a conceptual phase to commercial deployment phase with a successful implementation of the pilot plants on an industrial scale.
- Integrating mine water GSHP with an engine CHP system to recover heat from the engine coolant and maximise the performance of the whole GSHP system.
- The performance of the plant has been evaluated over a long period and has shown to be effective in converting an environmental liability into a low carbon energy resource.

8.5.2 Technical contribution

- Developed a software tool for an in depth technical design and commercial evaluation of a mine water based energy system.
- Detailed analysis of the data of the systems that includes theoretical case studies and actual data from the field trials.
- Developed a design to harness the energy from mine water, where the adverse effects of mine water on the equipment and the on the performance has been negated. The design supresses the formation of ochre in the raw mine water, which is the main culprit in causing

problems like clogging. The design is robust to function without hindrance and with minimum maintenance even when there is ochre in the raw mine water

8.6 Key findings

- This thesis has established that mine water can be very useful as an alternative source of energy for space heating which is reliable. This research work has tried to address the lack of field data available especially on the maintenance part with data from the field.
- This work has also shown that, with the design process employed here, mine water, which contains high levels of contaminants, can be managed without incurring any major maintenance issues.
- The operating costs are significantly less than conventional heating systems, 30 to 70 % less depending upon the competing conventional heating system.
- The carbon emissions are also significantly less than conventional heating systems, 30 to 70 % less depending upon the competing conventional heating system. This technology can help UK in meeting it carbon emission targets.
- Many of the local councils and other governmental agencies are still incurring significant costs in running the pumping stations and in treating the discharged water, even though the mines have closed down. By recovering the energy from these waters, a part of the operating costs can be offset. There are 64 such site available in UK alone, where the water is being pumped out daily and at some of these

sites, the pumping rate is more than 100 litres per second. These sites are ideal for having a mine water based heating system.

- Mine water based heating are ideal for district and community heating schemes and are easily scalable to small scale, medium scale and large scale, due to the availability of large volumes of mine water in the flooded coal mines under many towns and cities in the UK and in other parts of the world.

8.7 Summary

The GSHP using mine water is a good alternative method for space heating. The operating cost and carbon emissions are significantly lower than the conventional methods. Existing pumping stations and places where the water level has completely recovered are ideal to implement this technology, as most of the infrastructure is already in place, pumping costs are minimum and they can support large heating loads, the overall efficiency of the system will also be high. Care has to be taken to see that mine water is not exposed to air to prevent any maintenance issues due to ochre clogging. On the financial aspect of the project, initial cost of installation is significantly higher and only with the RHI payments the project looks feasible with respectable payback period.

8.8 Future work

8.8.1 Heating and cooling systems

Further work can be carried out to check the feasibility of using mine water for space heating and cooling (both the types, working simultaneously providing heating and cooling as well as working alternatively between heating and cooling). By having a heat pump that does heating and cooling, the utilisation of the system will be maximised, making it even more financially attractive with a lesser payback time. The COP of the system will be much higher in the simultaneous heating and cooling option.

8.8.2 District heating schemes

Mine water is ideal to be used for the district heating (as well as cooling, in warmer climates), as it is easily scalable to big loads. Feasibility studies and systems should be implemented and tested on a trial basis for a start.

9 References

1. Abu-Bakar, S.H., et al., 2014. Financial analysis on the proposed renewable heat incentive for residential houses in the United Kingdom: A case study on the solar thermal system. *Energy Policy,* 65, 552-561.

2. Athresh, A.P.,2015. *Borehole pump efficiency enquiry with the Coal Authority officials.*

3. Athresh, A.P., Al-Habaibeh, A. 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. *Energy Procedia,* 75, 1221-1228.

4. Athresh, A.P., Al-Habaibeh, A. and Parker, K., 2016. The design and evaluation of an open loop ground source heat pump operating in an ochre-rich coal mine water environment. *International Journal of Coal Geology,* .

5. Baik, Y., et al., 2014. Potential to enhance performance of seawater-source heat pump by series operation. *Renewable Energy,* 65, 236-244.

6. Bailey, M., et al., 2016. Heat recovery potential of mine water treatment systems in Great Britain. *International Journal of Coal Geology,* .

7. Banks, D., Pumar, A.F. and Watson, I., 2009. The operational performance of Scottish minewater-based ground source heat pump systems. *Quarterly Journal of Engineering Geology and Hydrogeology,* 42 (3), 347-357.

8. Banks, D., 2012. *An introduction to thermogeology: ground source heating and cooling.* John Wiley & Sons.

9. Banks, D., et al., 2004. Heat pumps as a tool for energy recovery from mining wastes. *Geological Society, London, Special Publications,* 236 (1), 499-513.

10. Banks, D., et al., 2003. Mine water as a resource: space heating and cooling via use of heat pumps. *Land Contamination & Reclamation,* 11 (2), 191-198.

11. Banks, D., et al., 1997. Mine-water chemistry: the good, the bad and the ugly. *Environmental Geology,* 32 (3), 157-174.

12. Bayer, P., et al., 2012. Greenhouse gas emission savings of ground source heat pump systems in Europe: A review. *Renewable and Sustainable Energy Reviews,* 16 (2), 1256-1267.

13. Bazargan Sabet, D., Demollin, E. and Van Bergermeer, J., 2008. Geothermal use of deep flooded mines. *In: Proceedings of Post-Mining Symposium, Nancy, France,* .

14. BGS, U., 2016. *Open Loop GSHP* [online]. . Available at: http://www.bgs.ac.uk/research/energy/geothermal/gshp.html [Accessed 08/10 2016].

15. Brown, I., Goodchild, J. and Collierv, C., 1979. THE COAL MINES OF THE FLOCKTON AREA NEAR HORBURY, WEST YORKSHIRE: REPORT OF FIELD MEETING, 9TH APRIL, 1978. *Bulletin of the Peak District Mines Historical Society Vol,* 7 (3), 169-173.

16. BS ISO 14686:2003,2003. ***Hydrometric determinations*****—** ***Pumping tests** for **water** wells—Considerations and guidelines for design, performance and use.* BS ISO.

17. Burnside, N.M., Banks, D. and Boyce, A.J., 2016. 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.

18. 'Burnside, N., et al., 2016. Hydrochemistry and stable isotopes as tools for understanding the sustainability of thermal energy production from a 'standing column' heat pump system: Markham Colliery, Bolsover, Derbyshire, UK. *International Journal of Coal Geology,* .

19. Cherrington, R., et al., 2013. The feed-in tariff in the UK: a case study focus on domestic photovoltaic systems. *Renewable Energy,* 50, 421-426.

20. Clausius, R., 1856. X. On a modified form of the second fundamental theorem in the mechanical theory of heat. *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science,* 12 (77), 81-98.

21. Coal Authority UK, 2016. *Coal Authority UK* [online]. . Available at: https://www.gov.uk/government/organisations/the-coal-authority [Accessed 05/05 2016].

22. Coldewey, W. and Semrau, L., 1994. Mine water in the Ruhr area (Federal Republic of Germany). *In: Proceedings of the 5th International Mine Water Congress,* pp. 613-629.

23. Connor, P.M., et al., 2015. The development of renewable heating policy in the United Kingdom. *Renewable Energy,* 75, 733-744.

24. Danfoss, 2016. *Danfoss BW10* [online]. . Available at: http://heating.danfoss.com/PCMPDF/BW10_PSD_Rev1.pdf [Accessed 08/20 2016].

25. David Banks, 2013. *Thermal Energy from mine workings* [online]. . Available at: http://www.gshp.org.uk/London/7_BanksGeothermalMinewater.pdf [Accessed 08/15 2016].

26. DECC,2015. ***Energy demand reduction in industry, business and the public sector****.*

27. DECC, U.,2014a. *Digest of United Kingdom energy statistics 2014.*

28. DECC, U.,2014b. *Energy Trends: June 2014.*

29. DECC, U., 2013. The future of heating: Meeting the challenge.

30. DECC, U., 2012a. The Future of Heating: A Strategic Framework for Low Carbon Heat in the UK.

31. DECC, U.,2012b. *UK renewable Energy roadmap update .* London: Department of Energy and Climate Change.

32. DECC, U.,2009. *The UK Renewable Energy Strategy .*

33. Department for Trade and Industry, UK, 2007. Meeting the energy challenge: A white paper on energy. *Department for Trade and Industry, Cm7124,* .

34. Department of Energy and Climate Change (DECC),2011. *Renewable Heat Incentive.* UK: DECC.

35. Derbyshire county council, 2016. *Markham Vale* [online]. . Available at: http://www.markhamvale.co.uk/downloads/markhamvaleschemebrochure.pdf [Accessed 08/20 2016].

36. Digges La Touche, G. and Preene, M., 2011. The potential use of ground energy in the mining industry–exploration to closure. *In: Proceedings of the 11th International Mine Water Association Congress–Mine Water–Managing the Challenges,* pp. 161-166.

37. Dimplex, 2016. *Heat pump seminar* [online]. . Available at: http://www.dimplex.co.uk/assets/Downloads_Documents/Heat_Pump_Seminars_V5.pdf [Accessed 07/26 2016].

38. Directive, E., 2003. 28/EC of the EU Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77. *EC And,* 30, 2009.

39. Dumpleton, S., 1996. The dangerous legacy of dead collieries. *In: International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts,* pp. 41A.

40. Earth river geothermal Ltd, 2016. *Earth river geothermal Ltd* [online]. . Available at: http://www.earthrivergeo.com/geothermal-hvac-loop-systems-information.php [Accessed 08/12 2016].

41. Earth Science, 2013. *Different types of mining* [online]. . Available at: http://jknightearthscience.blogspot.co.uk/2013/04/different-types-of-mining.html [Accessed 08/10 2016].

42. Econis Rewnewable Energy Solutions, 2010. *Econis Renewable Energy Solutions, Air Source Heat Pumps* [online]. . Available at: http://www.econicres.com/charts/airsourcel.jpg.

43. EngineersEdge, 2016. *Convective Heat Trasfer Coefficient chart* [online]. . Available at: http://www.engineersedge.com/heat_transfer/convective_heat_transfer_coefficients__13378.htm [Accessed 08/10 2016].

44. EurObserv, E., 2011. The state of renewable energies in Europe. *EurObserv'ER Report,* 11, 1-248.

45. Farr, G., et al., 2016. Low enthalpy heat recovery potential from coal mine discharges in the South Wales Coalfield. *International Journal of Coal Geology,* .

46. Faull, M., 2011. Plans for an Open-loop Heat-pump System at the National Coal Mining Museum for England. *In:* Plans for an Open-loop Heat-pump System at the National Coal Mining Museum for England. *National Coal Mining Museum for England Special Publications v. 13, Heat-pump Technology Using Minewater.* 2011, pp. 43-48.

47. Florides, G. and Kalogirou, S., 2007. Ground heat exchangers—A review of systems, models and applications. *Renewable Energy,* 32 (15), 2461-2478.

48. Florides, G. and Kalogirou, S., 2005. Annual ground temperature measurements at various depths. *In: 8th REHVA World Congress, Clima, Lausanne, Switzerland,* Citeseer, .

49. GEORGE L CHAPEL, 2001. *Gorrie's Fridge* [online]. . Available at: http://www.phys.ufl.edu/~ihas/gorrie/fridge.htm [Accessed 07/18 2016].

50. GI Energy, 2016. *Kingsmill hospital GSHP case study* [online]. . Available at: http://www.gienergy.net/downloads/casestudies/Kings_Mill_Hospital%20-%20GI_Case_Study.pdf [Accessed 08/15 2016].

51. Goodchild, J., 1983. *Caphouse Colliery and the Denby Grange Collieries: A History.* Wakefield Historical Publications.

52. Ground Source Heat Pump Association, 2016a. *The Advantages of GSHP* [online]. . Available at: http://www.gshp.org.uk/ground_source_heat_pumps.html [Accessed 08/20 2016].

53. Ground Source Heat Pump Association, 2016b. *GSHP domestic RHI* [online]. . Available at: http://www.gshp.org.uk/RHI_Domestic.html [Accessed 08/20 2016].

54. Ground Source Heat Pump Association, 2016c. *Non domestic RHI Tariff* [online]. . Available at: http://www.gshp.org.uk/RHI_Commercial.html [Accessed 08/20 2016].

55. Ground Source Heat Pump Association,2007. *Domestic Ground Source Heat Pumps. Design and Installation guide.* Ground Source Heat Pump Association.

56. Gzyl, G. and Banks, D., 2007. Verification of the “first flush” phenomenon in mine water from coal mines in the Upper Silesian Coal Basin, Poland. *Journal of Contaminant Hydrology,* 92 (1), 66-86.

57. Hall, A., Scott, J.A. and Shang, H., 2011. Geothermal energy recovery from underground mines. *Renewable and Sustainable Energy Reviews,* 15 (2), 916-924.

58. HealeyHero, 2016. *Website* [online]. . Available at: http://www.healeyhero.co.uk/rescue/pits/markham/markham_73_1.htm [Accessed 6/29 2016].

59. Henton, M., 1979. Abandoned coalfields: problem of pollution. *The Surveyor,* 153 (9), e11.

60. Henton, M.P., 1981. The Problem of Water Table Rebound After Mining Activity and its Effect on Ground and Surface Water Quality. *Studies in Environmental Science,* 17, 111-116.

61. homemicro, 2016. *http://www.homemicro.co.uk* [online]. . Available at: http://www.homemicro.co.uk/download/lzc_buffer.pdf [Accessed 7/26 2016].

62. INWATCO,2005b. *Integrated Water Management In Former Coal Mining Regions: Non-technical summary. Report.*

63. INWATCO,2005a. *Integrated Water Management In Former Coal Mining Regions: Guidance to Support Strategic Planning.*

64. Jamie David Macnab, 2011. ***A review of the potential thermal resource in Glasgow's abandoned coal mine workings.*** MSc., University of Strathclyde.

65. Jardón, S., et al., 2013. Mine Water for Energy and Water Supply in the Central Coal Basin of Asturias (Spain). *Mine Water and the Environment,* 32 (2), 139.

66. Jessop, A.M., MacDonald, J.K. and Spence, H., 1995. Clean energy from abandoned mines at Springhill, Nova Scotia. *Energy Sources,* 17 (1), 93-106.

67. Jo, H.Y., et al., 2001. Hydraulic conductivity and swelling of nonprehydrated GCLs permeated with single-species salt solutions. *Journal of Geotechnical and Geoenvironmental Engineering,* 127 (7), 557-567.

68. Kärkkäinen, S. and Oy, E., 2011. Heat pumps for cooling and heating. *Subtask 5, Report N: O,* 3.

69. Kindaichi, S., et al., 2015. Potential for using water reservoirs as heat sources in heat pump systems. *Applied Thermal Engineering,* 76, 47-53.

70. King, T.V., 1996. Environmental considerations of active and abandoned mine lands: lessons from Summitville, Colorado. *In: International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts,* pp. 94A.

71. Kruse, N.A.S., 2007. ***Simulation of Hydrogeochemical Processes in Abandoned Underground Mines.*** PhD., University of Newcastle Upon Tyne.

72. Langley, B.C., 2002. *Heat pump technology.* Prentice Hall.

73. Le Feuvre, P., 2007. *An investigation into ground source heat pump technology, its UK market and best practice in system design.* MSc., Strathclyde University.

74. Madiseh, S.G., et al., 2012. Sustainable heat extraction from abandoned mine tunnels: A numerical model. *Journal of Renewable and Sustainable Energy,* 4 (3), 033102.

75. Malolepszy, Z., Demollin-Schneiders, E. and Bowers, D., 2005. Potential use of geothermal mine waters in Europe. *In: Proceedings of the World Geothermal Congress,* pp. 1-3.

76. Malyszkz, 2011. *Plate Heat Exchanger* [online]. . Available at: https://en.wikipedia.org/wiki/Plate_heat_exchanger#/media/File:Plate_frame_1.svg [Accessed 08/15 2016].

77. Mark Johnson, 2006. *3-ton Slinky Loop* [online]. . Available at: https://commons.wikimedia.org/wiki/File:3-ton_Slinky_Loop.jpg [Accessed 08/12 2016].

78. Matthiessen T, 2011. *nyle systems* [online]. . Available at: http://www.nyle.com/downloads/Water-Heating-Summary.pdf [Accessed 08/10 2016].

79. McMullan, J.T. and Morgan, R., 1981. *Heat pumps.* Taylor & Francis.

80. National Grid, 2016. *STOR* [online]. . Available at: http://www.refworks.com/refworks2/default.aspx?r=references|MainLayout::init [Accessed 08/20 2016].

81. NCM, 2016. *National Coal Mining Museum website* [online]. . Available at: https://www.ncm.org.uk/ [Accessed 6/29 2016].

82. Neymeyer, A., Williams, R. and Younger, P., 2007. Migration of polluted mine water in a public supply aquifer. *Quarterly Journal of Engineering Geology and Hydrogeology,* 40 (1), 75-84.

83. Ochsner, K., 2012. *Geothermal Heat pumps: a Guide for planning and Installing.* Routledge.

84. OFGEM, 2016a. *Domestic RHI Tariff* [online]. . Available at: https://www.ofgem.gov.uk/environmental-programmes/domestic-rhi/contacts-guidance-and-resources/tariffs-and-payments-domestic-rhi/current-future-tariffs [Accessed 08/15 2016].

85. OFGEM, 2016b. *Non Domestic RHI Tariff* [online]. . Available at: https://www.ofgem.gov.uk/environmental-programmes/non-domestic-rhi/contacts-guidance-and-resources/tariffs-and-payments-non-domestic-rhi [Accessed 08/15 2016].

86. OFGEM, 2016c. *RHI* [online]. . Available at: https://www.gov.uk/government/policies/increasing-the-use-of-low-carbon-technologies/supporting-pages/renewable-heat-incentive-rhi [Accessed 7/13 2016].

87. OFGEM,2015. ***Guidance Volume One: Eligibility and How to Apply****.*

88. Oh, S., Cho, Y. and Yun, R., 2014. Raw-water source heat pump for a vertical water treatment building. *Energy and Buildings,* 68, 321-328.

89. Omer, A.M., 2012. *Performance analysis of ground source heat pumps for buildings applications*
. University of Nottingham.

90. Omer, A.M., 2008. Ground-source heat pumps systems and applications. *Renewable and Sustainable Energy Reviews,* 12 (2), 344-371.

91. Ordóñez, A., et al., 2012. Hydrogeological definition and applicability of abandoned coal mines as water reservoirs. *Journal of Environmental Monitoring,* 14 (8), 2127-2136.

92. Parker, K., 2011. Potential for heat pumps in Yorkshire and the rest of the United Kingdom. *Heat Pump Technology using Mine Water.(Wakefield: National Coal Museum.),* .

93. patagoniaalliance, 2016. *http://www.patagoniaalliance.org/wp-content/uploads/2014/08/How-much-water-does-an-Olympic-sized-swimming-pool-hold.pdf* [online]. . Available at: http://www.patagoniaalliance.org/wp-content/uploads/2014/08/How-much-water-does-an-Olympic-sized-swimming-pool-hold.pdf [Accessed 22/11/2016
.

94. Preene, M. and Younger, P., 2014. Can you take the heat?-Geothermal energy in mining. *Mining Technology,* 123 (2), 107-118.

95. 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 (11), 6783-6795.

96. Raymond, J. and Therrien, R., 2008. Low-temperature geothermal potential of the flooded Gaspé Mines, Québec, Canada. *Geothermics,* 37 (2), 189-210.

97. Reay, D.A. and Mac Michael, D.B., 1986. Heat pumps.

98. Robert Irving, 2013. *Assesing the potential of the heat pumps to reduce energy related carbon emissions from UK housing in a changing climate.* PhD., Oxford Brookes.

99. Rodríguez, R. and Díaz, M.B., 2009. Analysis of the utilization of mine galleries as geothermal heat exchangers by means a semi-empirical prediction method. *Renewable Energy,* 34 (7), 1716-1725.

100. Roijen, E., Op‘t Veld, P. and Demollin-Schneiders, E., 2007. The Minewaterproject Heerlen-low exergy heating and cooling in practice. *Palenc Aivc,* .

101. Saner, D., et al., 2010. Is it only CO 2 that matters? A life cycle perspective on shallow geothermal systems. *Renewable and Sustainable Energy Reviews,* 14 (7), 1798-1813.

102. Schofield, J., 2003. *Caphouse colliery: a brief mining history.* Wakefiled: National Coal Mining Museum for England.

103. Sheppard, T.H., 2005. A stratigraphical framework for the Upper Langsettian and Duckmantian of the East Pennine coalfields.

104. Sivasakthivel, T., Murugesan, K. and Sahoo, P., 2014. A study on energy and CO 2 saving potential of ground source heat pump system in India. *Renewable and Sustainable Energy Reviews,* 32, 278-293.

105. Sivasakthivel, T., Murugesan, K. and Sahoo, P., 2012. Potential reduction in CO 2 emission and saving in electricity by ground source heat pump system for space heating applications-a study on northern part of India. *Procedia Engineering,* 38, 970-979.

106. Sonntag, R.E., et al., 1998. *Fundamentals of thermodynamics.* Wiley New York.

107. Southwest Thermal Technologies Ltd., 2016. *BEM Shell and Tube Heat Exchanger* [online]. . Available at: http://www.shell-tube.com/Stainless-Steel/BEM_exchanger.html [Accessed 08/15 2016].

108. Stoertz, M.W., et al., 2001. Long-term water quality trends at a sealed, partially flooded underground mine. *Environmental & Engineering Geoscience,* 7 (1), 51-65.

109. Sudtharalingam, S., Hawkes, A. and Green, T., 2010. Feasibility of domestic micro combined heat and power units with real time pricing. *In: IEEE PES General Meeting,* IEEE, pp. 1-8.

110. Sumner, J.A., 1976. *Domestic heat pumps.* Prism Pr Ltd.

111. Sumner, J.A., 1948. The Norwich heat pump. *Proceedings of the Institution of Mechanical Engineers,* 158 (1), 22-29.

112. Technomine, 2016. *Underground conveyors* [online]. . Available at: http://technology.infomine.com/reviews/UndergroundHaulage/welcome.asp?view=full [Accessed 08/12 2016].

113. The Energy Saving Trust, 2016. *Energy prices* [online]. . Available at: http://www.energysavingtrust.org.uk/about-us/our-calculations [Accessed 08/20 2016].

114. The Met office, U.,2010. *The Met office, winter 2009/10, UK statistical summary, provisional graph of UK daily mean temperature of winter 2009/10 (december, january and february).*

115. UNFCCC, 2014. *Kyoto Protocol* [online]. . Available at: http://unfccc.int/kyoto_protocol/items/2830.php [Accessed 7/12 2016].

116. United Nations Framework Convention on Climate Change, 2015. Paris Agreement, *Paris, France,* .

117. US Department of Energy, 2016a. *ELECTRIC RESISTANCE HEATING* [online]. . Available at: https://energy.gov/energysaver/electric-resistance-heating [Accessed 11/22 2016].

118. US Department of Energy, 2016b. *Vertical Slinky* [online]. . Available at: http://energy.gov/energysaver/geothermal-heat-pumps [Accessed 08/12 2016].

119. Verhoeven, R., et al., 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.

120. Viessmann UK,2012. *Heat Pump Technical Guide.*

121. Watzlaf, G.R. and Ackman, T.E., 2006. Underground mine water for heating and cooling using geothermal heat pump systems. *Mine Water and the Environment,* 25 (1), 1-14.

122. wellowner.org, 2016. ***Geothermal Heat Pump Systems*** [online]. . Available at: http://www.wellowner.org/geothermal-heat-pumps [Accessed 08/12 2016].

123. Wilcockson, W.H., 1950. *Sections of Strata of the Coal Measures of Yorkshire: T.* Sheffield: Midland Institute of Mining Engineers;.

124. Wood, S., Younger, P. and Robins, N., 1999. Long-term changes in the quality of polluted minewater discharges from abandoned underground coal workings in Scotland. *Quarterly Journal of Engineering Geology and Hydrogeology,* 32 (1), 69-79.

125. WPS Submersible pump, 2016. *WPS 12, submersible pump* [online]. . Available at: http://www.proquipdirect.com/ekmps/shops/pqonline/resources/Other/curves-data.pdf [Accessed 08/20 2016].

126. Younger, P.L., 2014. Hydrogeological challenges in a low-carbon economy. *Quarterly Journal of Engineering Geology and Hydrogeology,* 47 (1), 7-27.

127. Younger, P.L., 2008. Towards regulatory criteria for discharging iron-rich mine water into the sea. *Mine Water and the Environment,* 27 (1), 56-61.

128. Younger, P.L., Banwart, S.A. and Hedin, R.S., 2002. Mine Water Hydrology. *In:* Mine Water Hydrology. *Mine Water.* Springer, 2002, pp. 127-270.

129. Younger, P., 1998. Coalfield abandonment: geochemical processes and hydrochemical products. *Energy and the Environment.Geochemistry of Fossil, Nuclear and Renewable Resources.Society for Environmental Geochemistry and Health.MacGregor Science, Insch,* , 1-29.

130. Younger, P., 1993. Possible environmental impact of the closure of two collieries in County Durham. *Water and Environment Journal,* 7 (5), 521-531.

131. Younger, P., Arnell, H. and Griffin, J., 1998. Hydrological consequences of the abandonment of regional mine dewatering schemes in the UK. *In: Hydrology in a changing environment. Poster papers and index, int. symp. organised by the British Hydrological Society,* pp. 6-10.

132. Younger, P. and Bradley, K., 1994. Application of geochemical mineral exploration techniques to the cataloguing of problematic discharges from abandoned mines in north-east England. *In: Proceedings of the 5th International Minewater Congress, Nottingham,* pp. 857-871.

133. Younger, P.L., 1997. The longevity of minewater pollution: a basis for decision-making. *Science of the Total Environment,* 194–195, 457-466.

134. Younger, P.L., 2016. A simple, low-cost approach to predicting the hydrogeological consequences of coalfield closure as a basis for best practice in long-term management. *International Journal of Coal Geology,* 164, 25-34.

Appendices

Applied Energy 211 (2018) 393–402

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Performance analysis of using mine water from an abandoned coal mine for heating of buildings using an open loop based single shaft GSHP system

Amin Al-Habaibeh[a,*], Anup P. Athresh[a], Keith Parker[b]

[a] Innovative and Sustainnable Built Environment Technologies Research Group (iSBET), Nottingham Trent University, NG1 4BU, UK
[b] Alkane Energy Plc, Edwinstowe House, Edwinstowe, Nottingham NG21 9PR, UK

HIGHLIGHTS

- Water from flooded coal mines can be used for low-carbon heating and cooling applications.
- A single shaft is used to extract the warm water for heating applications, hence reducing cost and complexity.
- The results show that the technology provides high and stable COP levels due to constant temperature of the coal mine.
- Flooded coal mines provide sustainable technology and could enhance community engagement.

ARTICLE INFO

Keywords:
GSHP
Sustainability
Community engagement
District heating
Open loop
Mine water
Low carbon technology

ABSTRACT

The application of ground source heat pumps (GSHP) for heating and cooling of buildings is currently increasing in popularity in the UK and globally. Traditional GSHP systems use the naturally available geothermal gradient of earth for heating and cooling purposes using open loop or closed loop systems. In this paper, the use of mine water from a flooded coal mine for heating of buildings is presented using a GSHP system with an open loop configuration. The novelty of this approach is that a single shaft is used to extract the warm water and inject the cooler water back into the same shaft, thereby minimising the area needed, initial capital costs in constructing a doublet system and also potentially overcome the time consuming process to address related environmental agencies regulation regarding the discharging of the mine water. The relatively stable temperature low enthalpy of mine water contained in the abandoned and flooded coal mines are ideal to be used for both heating and cooling of buildings when used in conjunction with heat pumps. The GSHP is considered to be an effective means of reducing the carbon emission as it gives more output in the form of thermal energy in comparison to the electrical energy it consumes as input. This research work reports on the performance of the system over the winter season and its long term potential in converting the mine water from an environmental liability to a sustainable energy resource and offers a means to regenerate the former coal mining areas.

1. Introduction

The existence of flooded coal mines in many of the industrialised nations is a legacy left behind by the industrial revolution, that occurred on the back of coal mining over the past 200 years. The UK is one of the best examples to see the legacy of the abandoned and flooded coal mines. The coal mining played a pivotal role in UK becoming one of the leading economies in the world on the back of the industrial revolution. Communities in towns and villages surrounding the mines flourished and became prosperous providing employment to thousands of people. This trend later spread to the other countries in Europe.

When the mines were in operation, deep mining of coal involved going further below the water table to extract the coal, this involved continuous pumping of water from the lower geological regions containing the coal seams, this was done to keep the underground seams dry, so that miners could work safely [1]. The pumps were placed at strategic locations within and around the mine complex and dewatering caused a disruption to natural hydrogeological conditions [2]. The pumped water was discharged into the water bodies after removing the suspended particles, iron and other effluents, most often the dewatering operation of an active mine had a big impact on the subsurface hydrogeology [1]. The majority of the coal mines in the UK and other industrialised nations of Western Europe were closed down at the end of 20th century due to economic and political reasons [3–5]. The

* Corresponding author.
E-mail address: Amin.Al-Habaibeh@ntu.ac.uk (A. Al-Habaibeh).

https://doi.org/10.1016/j.apenergy.2017.11.025
Received 16 February 2017; Received in revised form 1 November 2017; Accepted 2 November 2017
Available online 18 December 2017

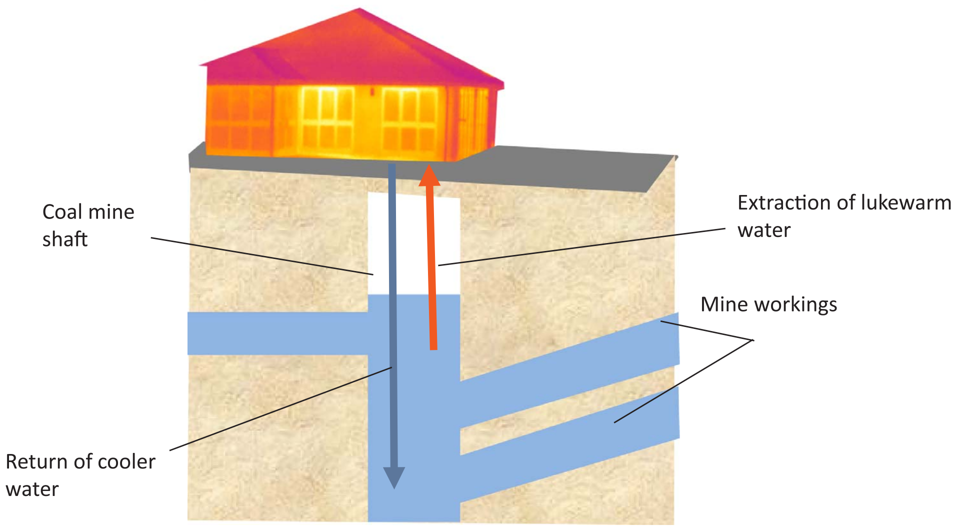


Fig. 1. A schematic diagram of a single shaft coal mine GSHP system.

closure of the collieries led to the termination of pumping as well. Ending of dewatering leads to a gradual recovery of the water level to its initial levels and subsequently filling up the created void spaces due to the extraction of coal with water, leading to dissolution of efflorescent salts that develop in the drained and ventilated areas due to the pyrite oxidation. This causes deterioration in the quality of water in the abandoned workings after the closure of the colliery [6–10]. The quality of the mine water improves but takes a long time which can range from couple of years to couple of decades [7,11–13]. The raising water levels pose a threat to the ground and surface water resources and endanger the local ecology [10,14]. There have been instances where surface discharge has occurred and has contaminated the rivers [15], fresh water aquifers [16] and marine environments [17]. In order to prevent mine water from coming in contact with the clean water bodies, the water in most cases is still being pumped even after the closure of mines. In UK, for example, there are 64 sites where the water is being actively pumped [18].

Considerable theoretical and academic studies have been carried out to estimate the thermal energy potential of mine water in flooded coal mines [19–25]. The mining operations created a vast network of shafts, tunnels and workings underground and since their abandonment, they are now filled with water. The temperature of the water is often reaches several degrees centigrade above the annual average air temperature. Normally, the temperature of the ground at a depth of about 100 m in the UK is circa 13–14 °C [26].

In spite of the obvious economic and environmental benefits, only 28 such schemes have been documented and only 57% of them were coal mine based [27]. A detailed description of the operational concepts of heat pumps, types and configurations has been presented in references [28–29]. The recent advances in heat pump technology have been described reference [30]. The theoretical concepts of using the mine water for heating and cooling applications have been described in several references, see for example [3,26,31–33]. Moreover, an educational lab-based simulator to demonstrate mine water heating has been described by the authors [33]. A review and details of the existing and proposed mine water based heating and cooling installations throughout the world has been described by [20,23]. A comparison of mine water heating and cooling systems with other technologies along with existing and potential sites in North America has been discussed, and the results show a promising potential [19]. An analysis of important parameters impacting the commercial feasibility of a GSHP in North America has been described in [34]. A mine water based heating scheme operating since 1989 at Nova Scotia in Canada with successful results has been presented in literature [35]. Ref. [36] describes a large scale mine water heating scheme in Spain, where heating and cooling is being provided to a university building and a hospital, it also describes the possibility of using the discharged water for domestic and industrial applications thereby offering solutions to the mine water discharge problems as well. A comprehensive list of the existing mine water based energy systems has been described in [37]. In the UK, the performance of a mine water based heating system implemented in a housing estate in Scotland has been described [38], in this region an estimated potential of about 12 MW of heat can be harnessed from the Midland Valley of Scotland [39]. The UK's Coal Authority operates a number of pumping stations at various locations throughout UK, pumping large volumes of water from the abandoned coal mines and an estimated 55 MW of heat can be extracted from those discharged water [39–40]. Refs. [41–43] presents an example of how a discharged mine water is suitably being harnessed at the Caphouse Colliery in the UK. A pilot district mine water heating and cooling scheme has been successfully implemented in the Dutch town of Heerlen and the details of this scheme has been described in [44]. Following the success of the pilot scheme, the scheme was upgraded to a full scale sustainable energy system [45]. The scheme at Heerlen has been very fruitful as it shows how a former mining town facing a social and economic crisis following the closure of the mines has successfully managed to transform itself using the mine water heating and cooling scheme to a sustainable energy hub attracting both public and private investments. Heerlen project has shown the way forward to other mining towns around the world still struggling with energy poverty and mine closures, with this community engagement. Other related applications of GSHP in literature also include the use of spiral loop ground heat exchanger (GHE) for a solar-assisted ground source heat pump with support from artificial neural network (ANN) and adaptive neuro-fuzzy inference system (ANFIS) for modelling [46]. The results show that the ANFIS is more successful than that of ANN in forecasting performance of the solar ground source heat pump system. In [47–48] GSHP has been used to investigate snow melting on pavements experimentally and using simulation. Cost vs benefits has been found to be essential to consider such applications. Other applications of GSHP have included the use of spiral type heat exchanger as a standalone greenhouse heating system [49].

The application GSHP for mine water and optimising the performance of the system through a reliable system design requires the availability of high quality data. The concept of using mine water from an abandoned coal mine using a single shaft system, see Fig. 1, to extract and inject the water has been previously outlined by the authors [50–52]. This paper describes the detailed performance of the system, at Alkane Energy site in Markham, over the winter season when it is utilised for heating the buildings.

2. Methodology and site location

This paper aims to investigate the practicality and performance of extracting energy from flooded coal mines using a single mine shaft to extract the relatively warm water and return the cooler mine water back into the same shaft. For that reason Markham coal mine has been selected. Markham coal mine was one of the main collieries in UK and operated from 1905 until its closure in 1993. The underground coal seams were accessed through four shafts present in the colliery complex. After the closure of the mine three of the four shafts were filled, the No. 3 shaft being left open to vent mine gas. This shaft was subsequently utilised by Alkane Energy to extract Coal Mine Methane (CMM) for the purpose of electricity generation. In 2006 the rising mine water caused the methane flow to cease. Alkane Energy converted this site as their control centre and a maintenance depot, from where they could control all their operations across the various sites remotely. The water from the Markham Colliery is now being used to heat the site buildings of the Alkane Energy at Markham through a GSHP. The study methodology is based on practically heating two buildings over the winter months to investigate a wide range of variables and parameters. COP values, water temperature stability and energy extracted were among the parameters monitored and assessed.

3. GSHP system description

A schematic diagram of the mine water heating system in consideration is as shown in the Fig. 2. The detailed description of the system has been given in [50]. The GSHP system consist of a single 20 kWh commercial Danfoss heat pump, counter flow shell and tube type heat exchanger, a 300 l buffer tank, mesh filter and pipes connecting all the different units. The borehole pump is installed in the mine shaft at a depth of 170 m below ground level. The return hose of the borehole is at a depth of 150 m below ground level. As a safety mechanism the methane in the mine shaft is monitored and would shut down the system if the methane level crosses a pre-set level.

4. Instrumentation and monitoring of the system

The main parameters which need to be monitored are energy consumption and heat transfer rates between the mine water and the brine, see Fig. 2, and these are determined by measuring the instantaneous fluid flow rate and both out and return temperatures. Energy metres are installed to measure the electricity consumption of the heat pump and mine water pump. Kamstraup heat metres are used to monitor both the mine water and the heat pump output parameters. The heat meter measures the flow rate in l/h, ΔT of the water in °C, instantaneous energy in kW and cumulative energy in MWh. The Kampstraump heat meter consists of an integrated flow and temperature sensors and an integrator to calculate the energy based on the flow and temperature values. The entire monitoring system is connected to the internet for remote data capture and analysis. Fig. 3 presents some of the main parts of the instrumentation of the system.

5. Main performance indicators

When a heat pump is used, it requires energy to drive the

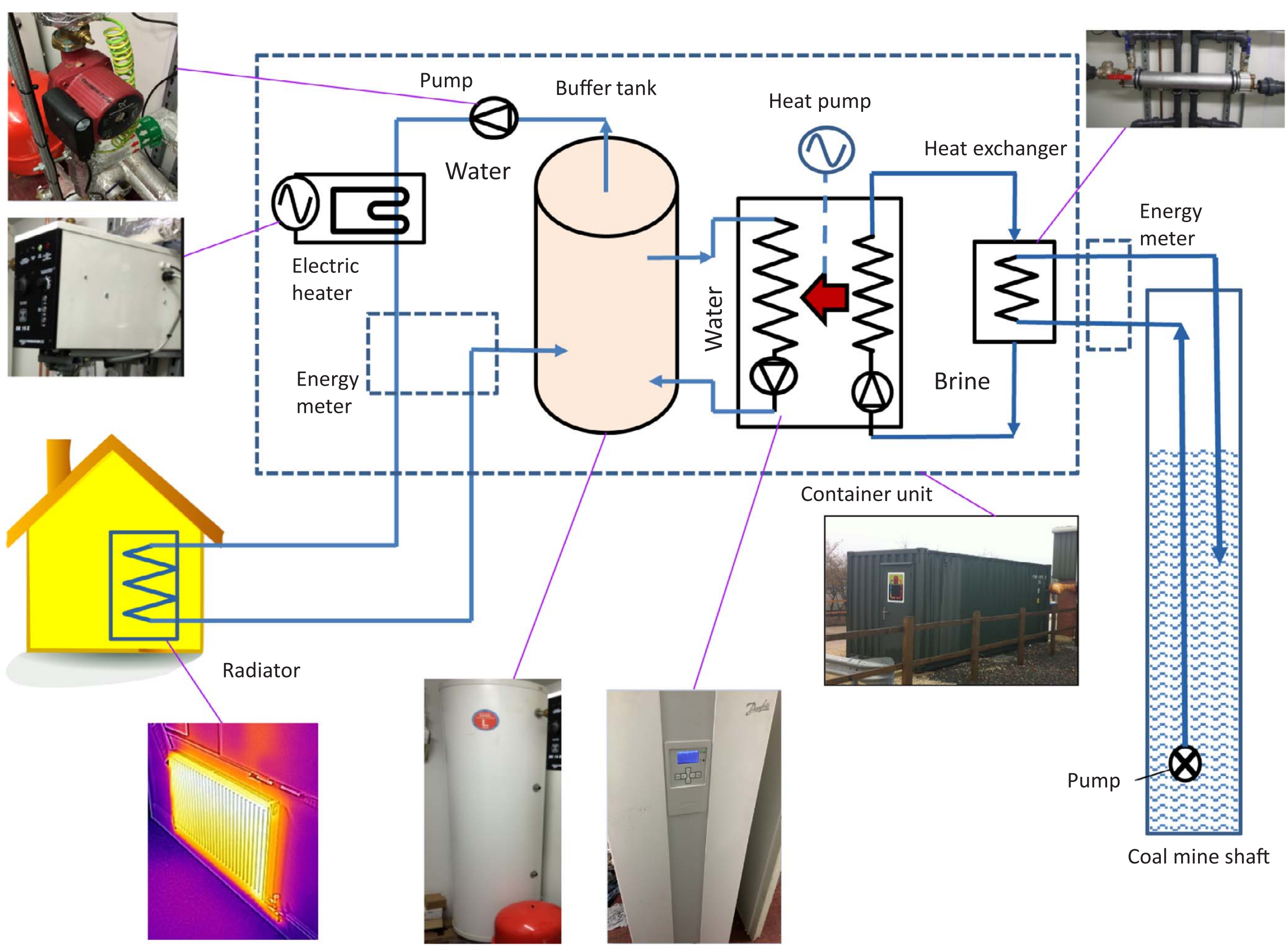


Fig. 2. A simplified schematic system of the single shaft GSHP system at Markham, UK.

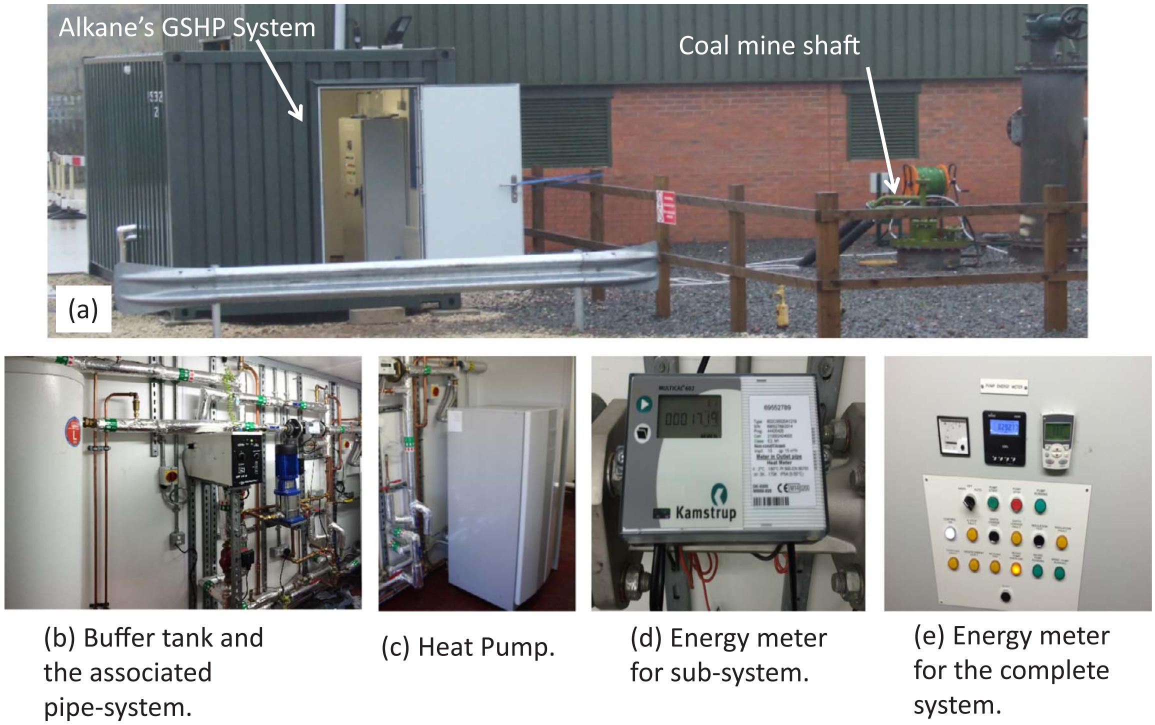


Fig. 3. Alkane's GSHP system (a), buffer tank and the associated pipe-system (b), heat pump (c), the energy meter for the coal mine water (d), the energy meter for the complete system (e).

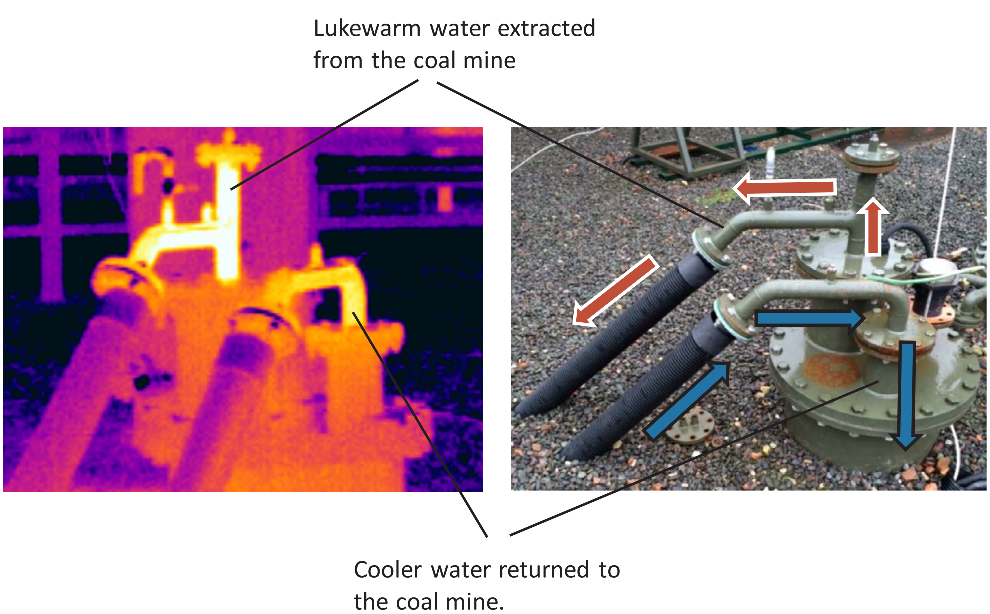


Fig. 4. Infrared image of the extraction and return lines (left) and the corresponding visual image (right).

compressor, and the efficiency of operation of the heat pump must be taken into consideration. The efficiency of a heat pump is referred to as its coefficient of performance (COP), it is expressed as the ratio of the heat energy delivered to the electrical energy used to drive the heat pumps. The COP delivered by a given heat pump will depend on the relative input and output temperatures [53]. In normal operation COP's vary in the range of 3–6 [54]. The thermal energy output and electricity consumed by the heat pump mainly depends upon the heat transfer between the mine water and brine, brine and evaporator of the heat pump and between the condenser of the heat pump and the building's heating fluid. Fig. 4 shows the difference in temperature between the extraction and return line of the mine water taken through using infrared thermography.

Energy that can be extracted from the mine water can be calculated using Eq. (1):

$$Q_{mw} = m_{mw} \cdot C_p \cdot \Delta T kJ \tag{1}$$

where Q_{mw} is the thermal energy of mine water in kJ, m_{mw} is mass of mine water in kg, C_p is the specific heat of water (4.18 kJ/kg K) and ΔT is the difference in temperature in Kelvin.

Efficiency or COP of the heat pump is calculated using Eq. (2):

$$\text{COP}_{Heatpump} = \frac{Q_{HP}}{W_{HPelectrical}} \tag{2}$$

where $W_{HPelectrical}$ is the electrical power consumption of heat pump in kJ and Q_{HP} is the thermal energy output produced by the heat pump in kJ,

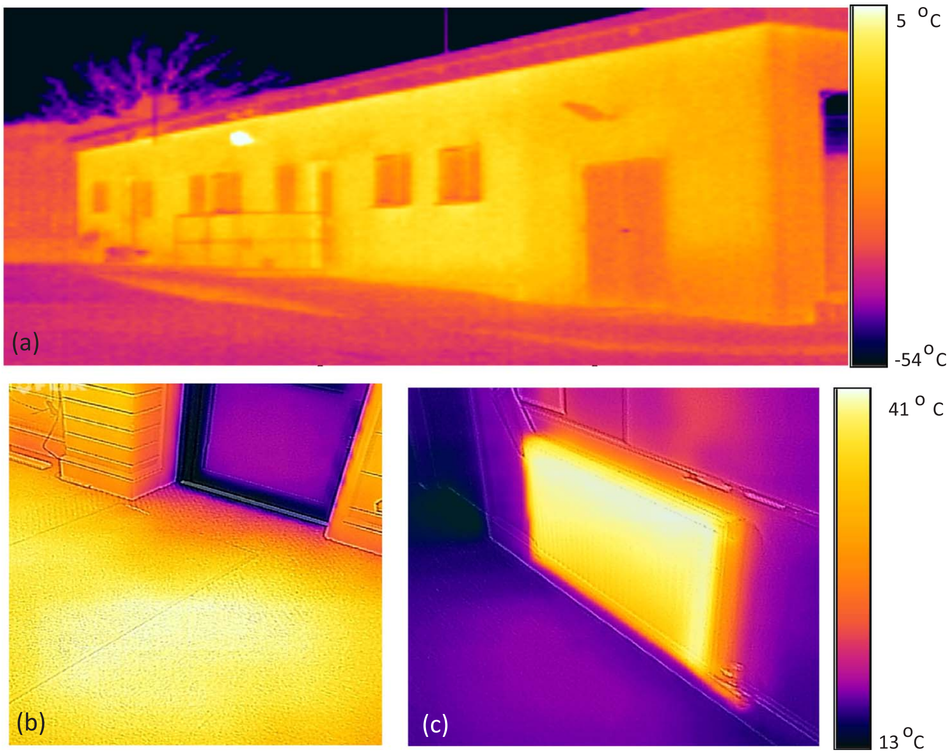


Fig. 5. Infrared image of the heated building (a), under floor heating (b) and normalized radiator heating (c).

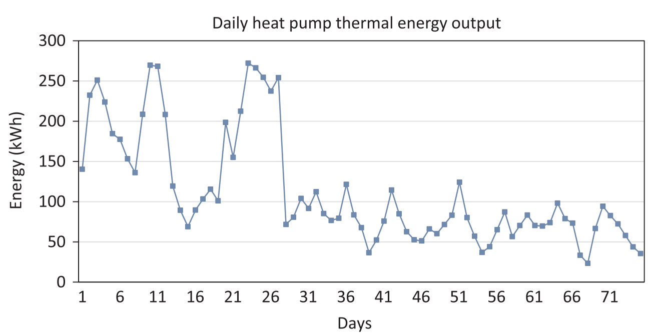


Fig. 6. The daily thermal energy output of the heat pump during the 71 days of winter operation.

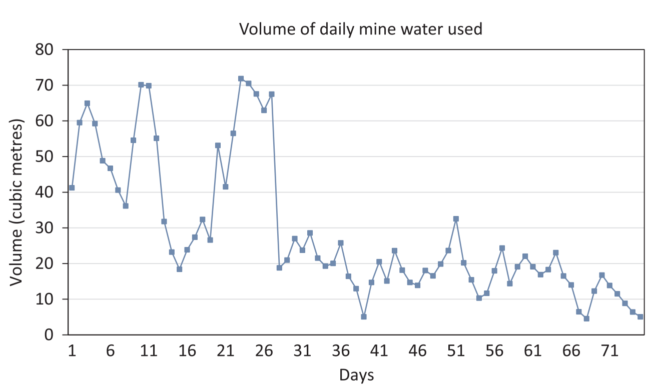


Fig. 7. The daily volume of mine water used for heat generation.

expressed as:

$$Q_{HP} = m_{HP}{\cdot}C_p{\cdot}\Delta T kJ \quad (3)$$

Given that m_{HP} is mass of water circulated in kg, C_p is the specific heat of water (4.18 kJ/kg K) and ΔT is the difference in temperature in Kelvin.

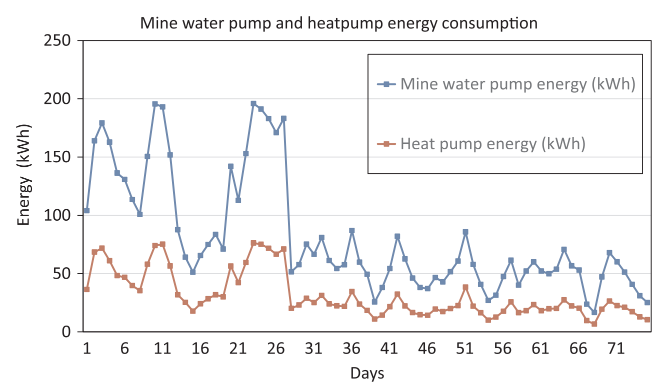


Fig. 8. Daily energy usage by the heatpump and mine water pump.

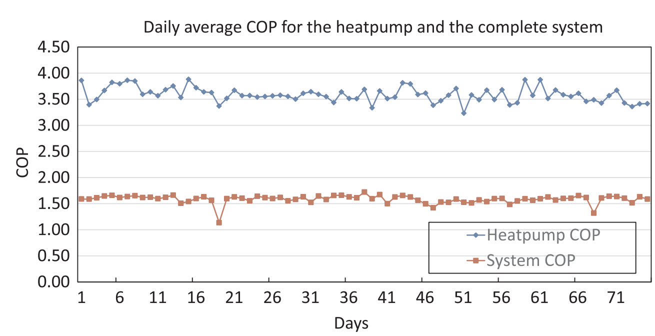


Fig. 9. Daily average COP of heatpump and of the whole system.

Efficiency or COP of the system includes the energy consumed by the heat pump, mine water pump and the circulation pump and it is calculated using Eq. (3).

$$COP_{system} = \frac{Thermal\ Energy\ produced\ by\ system\ in\ \mathrm{kJ}}{Electrical\ Energy\ consumed\ by\ system\ in\ \mathrm{kJ}} \quad (4)$$

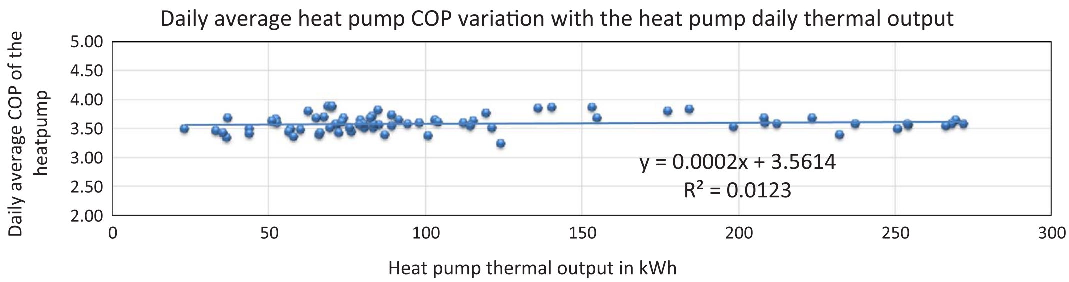


Fig. 10. The relationship between heat pump COP and daily thermal output of the heat pump.

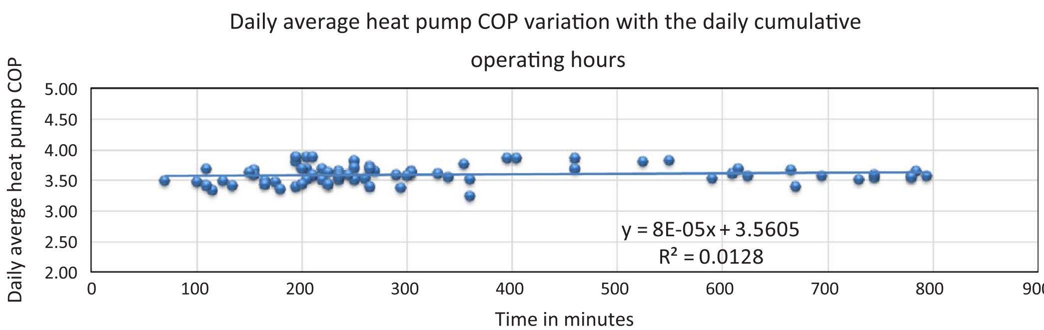


Fig. 11. The heat pump COP variation for different operating hours.

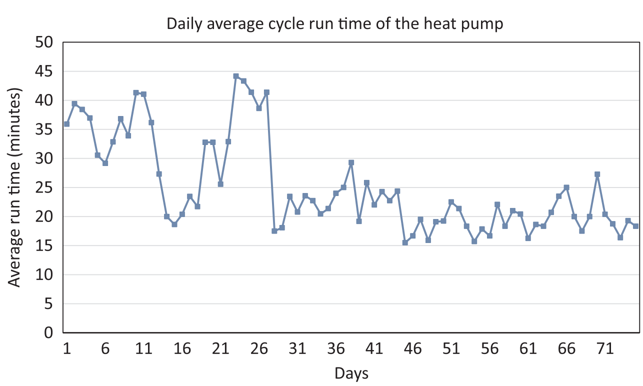


Fig. 12. The daily average operational time (cycle time) in minutes of the heat pump.

$$COP_{system} = \frac{Q_{HP}}{W_{HPelectrical} + W_{CPelectrical} + W_{MPelectrical}} \quad (5)$$

where $W_{CP\ electrical}$ is the energy consumed by the circulation pump in kJ and $W_{MP\ electrical}$ is the energy consumed by the mine water pump in kJ.

COP of the whole system is the ratio between the energy produced by the heat pump and energy consumed by the system and includes the electricity consumed by the heat pump, mine pump and circulation pumps, see Fig. 2. The compressor is the main component in the heat pump that consumes most of the electricity and small amount of electricity is also consumed by circulation pumps to circulate the fluid within the heat pump. The electricity consumption of the heat pump will depend on its design and the efficiency which is based on the input and output level of temperatures of the fluids entering and leaving the heat pump. The other important parameters that impact the overall efficiency are the depth of water in the coal mine (if the water level in the mine is deep then significant amount of energy will be consumed to pump the water to ground level) and the distance through which the hot water has to be transported from the heat pump to the recipient building.

6. Results and discussion

The performance of the GSHP system operations over the winter period is presented in this paper. Fig. 5 presents the infrared thermography images of one of the heated buildings and under floor heating and the normal radiator. During the period of winter testing, the average efficiency (COP) of the heat pump is found to be 3.59 and the overall efficiency of the system is 1.59. The efficiency is affected by a number of dynamic factors including outside ambient temperature, inside room temperature, heat pump outlet hot water temperature, temperature of the mine water being extracted. The power consumed by the borehole pump has a big impact on the overall system efficiency, if the heat pump efficiency is considered constant.

Fig. 6 presents the daily fluctuation of the thermal output from the

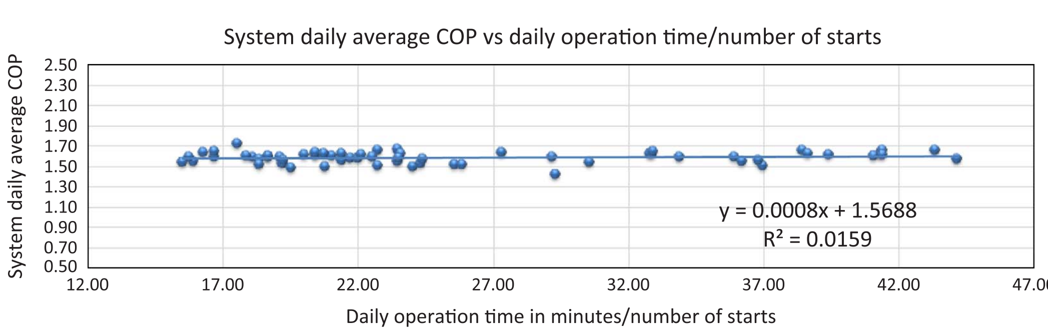


Fig. 13. The relationship between the system's COP and the duration of each run (cycle time).

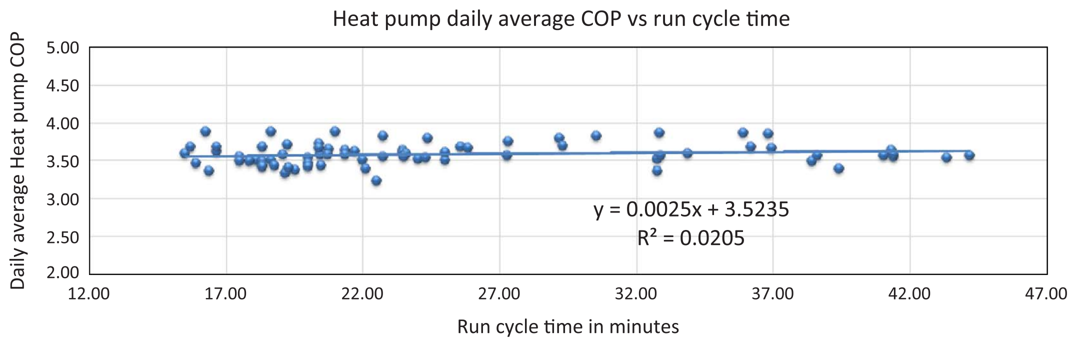


Fig. 14. The relationship between heat pump's COP and duration of average run time (cycle time).

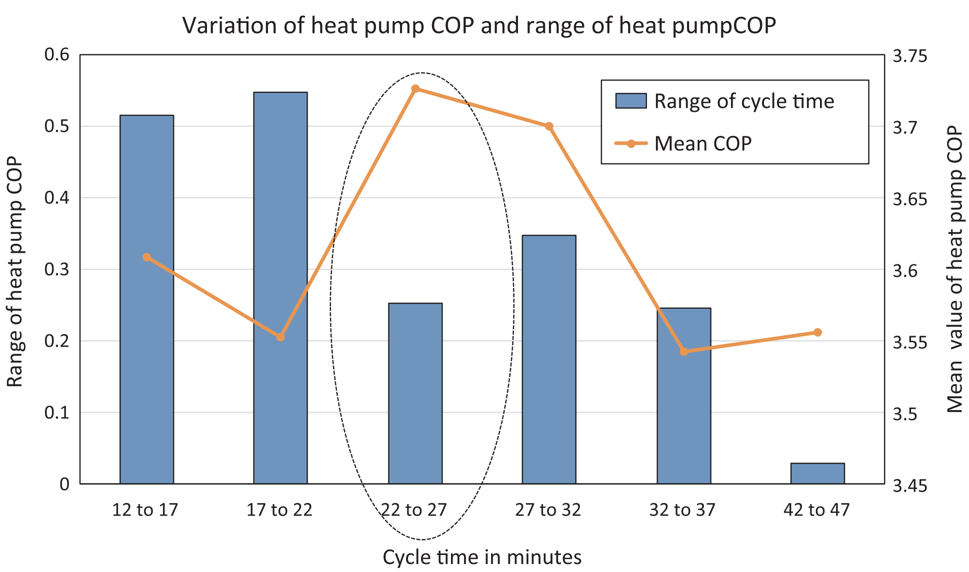


Fig. 15. The variation of COP with run time of each cycle (duration of which the compressor of the heat pump in continuous operation).

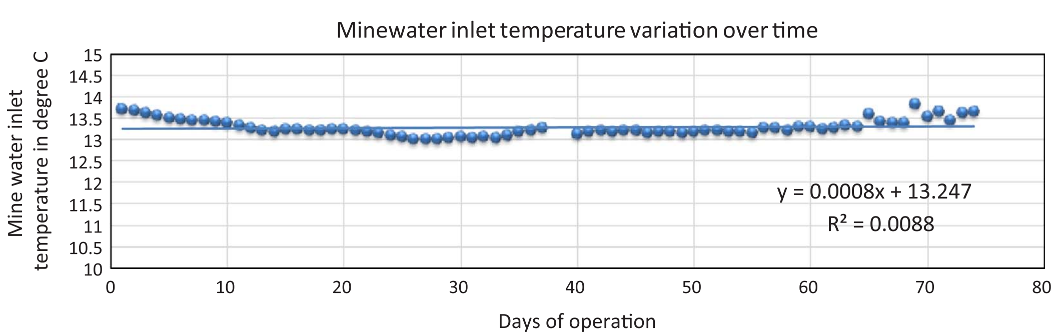


Fig. 16. The daily average mine water inlet temperature values over time.

heat pump, it varies between 276 kWh and 30 kWh. Fig. 7 shows the fluctuation in the volume of water that is pumped daily, when more heat is needed, more water will be pumped to extract the required energy. Fig. 8 shows the electric consumption of the heat pump and the mine water pump. Figs. 9 and 10 show that it is possible to get a good and a stable COP of circa 3.5 for most of the time from a GSHP, when mine water is used. The COP values of the GSHP tends to be on a higher side as the heat demand increases and the GSHP's are run for a longer durations at each operational cycle.

Lower values of COP for the heat pump is attributed to the lower heat demand (running at sub optimal conditions) from the building, this results in cycling of the compressor of the heat pump. Fig. 11 shows that there is some fluctuation in total number of hours the heat pump has operated each day, the longer the operating hours, the higher COP. As the heat pump runs for a longer duration in each cycle, the cycling (on/off) of the heat pump compressor is reduced.

Fig. 12 shows the variation in average operating cycle hours through the testing period. Figs. 13 and 14, shows the variation in COP of the whole system and the heat pump, due to the fluctuation in the operating time of each cycle (time during which the compressor in continuous operation). The COP values tend to be slightly higher as the operating time of each cycle increases. Fig. 15, shows further analysis indicating that when the operating cycle time in each run increases, the average COP increases and reaches the peak value of 3.72. When the average of a single run cycle time is between (22–27 min) and the COP value reaches its maximum average. The range of average COP value at each run; i.e. the difference between the maximum and minimum values, at various run times shows that smaller range values occur at a longer duration of run time. Fig. 15 indicates that there is an optimum run-time domain to deliver high COP with high stability (in this case

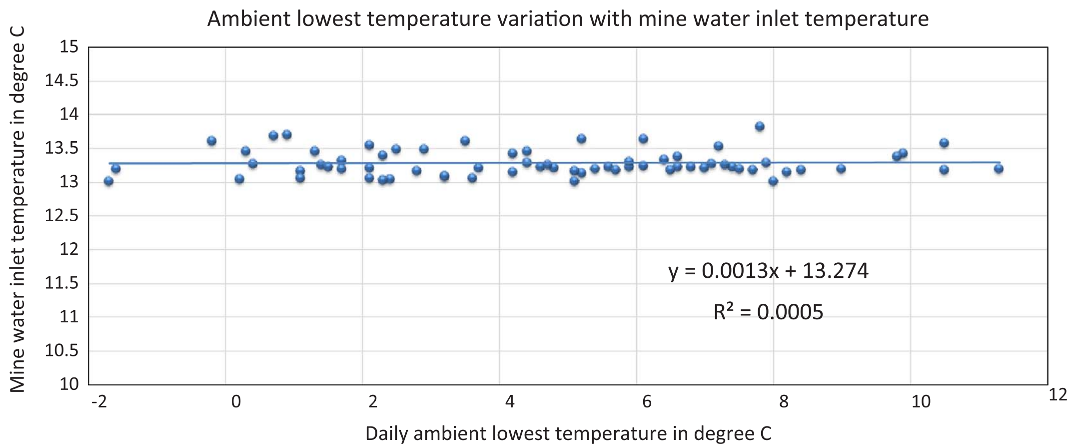


Fig. 17. The mine water inlet temperature variation in relation to the lowest ambient temperature.

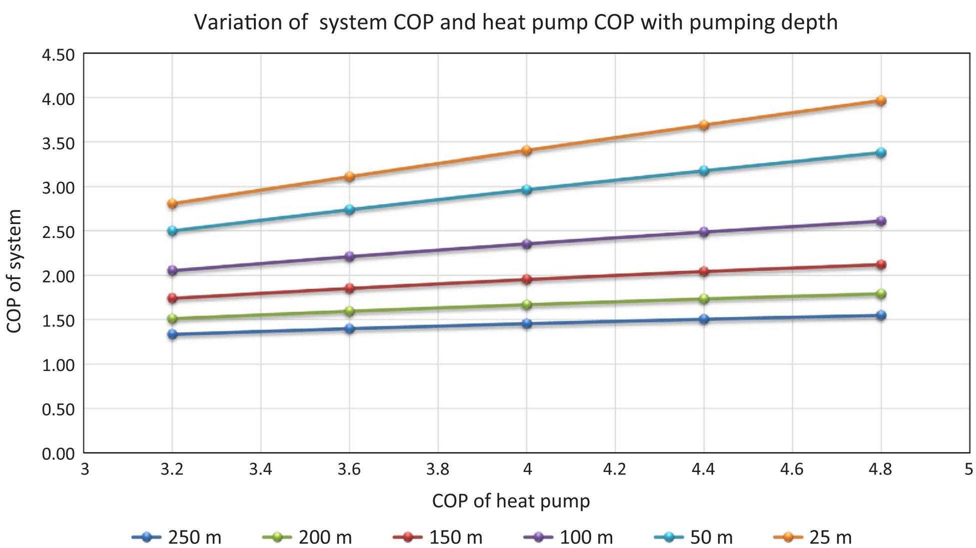


Fig. 18. The relationship between the depth of water in the coal mine, COP of the heat pump and COP of the system.

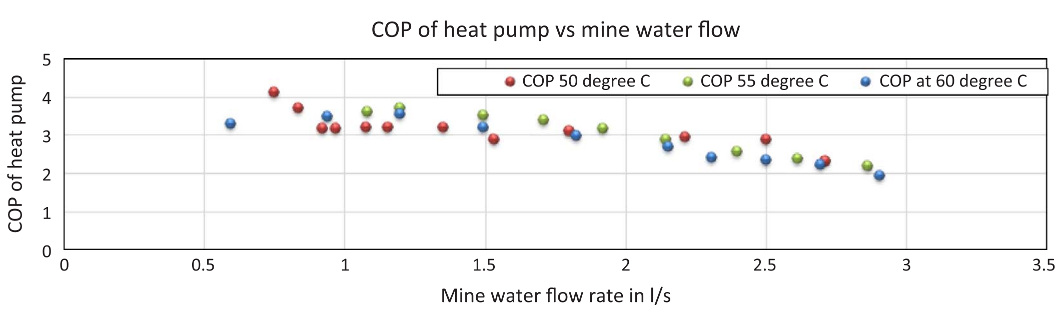


Fig. 19. The relationship between mine water flow rate and COP of the system at different output temperatures.

22–27 min); any deviation from that will deliver lower COP and lower stability (i.e. a higher range).

The results show that temperature of the incoming mine water has remained stable during the operation. Figs. 16 and 17 indicate that there are no significant variation in the incoming mine water temperature over time, suggesting that the mine water energy is constantly replenished by either the geothermal rocks or the fresh inflow of warm water into the mine shaft from other coal seams. The mine water in the abandoned coal mines therefore represents a huge reservoir of low enthalpy water and is a reliable and secured source of energy which can be used profitably used for heating and cooling applications in a long run without any loss in its energy content.

Fig. 18 presents the relationship between the depth of water in Markham and its expected relationship with the COP values of heat pump and the COP of the whole system based on the obtained experimental results. At a depth of 100 m, the overall COP value is about 2.7, when the COP of the heat pump is 4.8. This means for every 1 KWh consumed by the system, 2.7 KWh is produced as an output. The difference in energy is the energy extracted from the water of the mine. Due to the rising water level in the shaft, the overall COP is expected to reach a value of approximately 3.97 at a depth of 25 m, with the heat pump COP reaching 4.8. Fig. 19 presents the relationship between the flow rate of coal mine water and the COP of the system at different target output temperatures. It is evident that the increase in the flow rate will reduce the COP of the system for a given heating demand since no further energy will be extracted from the coal mine water, but increasing the mine pump power consumption. Also the increase in the target temperature will reduce the COP since the increase in temperature will increase the work needed by the heat pump to transfer the heat to a higher energy level.

7. Conclusion

This paper has presented a detailed analysis of using energy from flooded coal mines at Alkane Energy Markham site using a single shaft system. The analysis of the system's performance has indicated that the temperature of the mine water and the depth of water in the coal mine have a significant impact on the overall COP of the system, with the water level in the abandoned mines rising, the overall efficiency can only get better. The COP of the heat pump depends on the temperature of the incoming mine water, flow rate of mine water, heat demand from the building, ambient atmospheric temperature, optimum sizing of buffer tank and the hot water outlet temperature of the heat pump. The temperature of the mine water remains stable and does not vary over time from energy use or ambient temperature. Other benefits of using a single shaft open loop system is the reduced area needed on the site for the system, low capital investment costs as the need to have a second borehole to discharge water is eliminated. On the licensing and permitting side, since the mine water extracted is being injected back to its original source without altering its chemical properties, it is easier to get a consent from local authorities and also eliminates a potential problem of depleting the mine water level, which can have a major impact on the long term efficiency (COP) of the system. Water from flooded coal mines can be valuable source of low carbon energy especially in former Brownfield mining regions which are can be regenerated into new industrial, commercial and housing developments which have substantial heating and cooling needs.

Acknowledgments

The authors would like to thank Alkane Energy Ltd for their support. This paper is based on field research carried out within the frame of research project: Low-Carbon After-Life (LoCAL) financed by the European Commission, Research Fund for Coal and Steel, July 2014–June 2017 (Contract No.: RFCR-CT-2014-00001).

References

[1] Younger PL. A simple, low-cost approach to predicting the hydrogeological consequences of coalfield closure as a basis for best practice in long-term management. Int J Coal Geol 2016;164:25–34.
[2] Younger PL, Banwart SA, Hedin RS. Chapter three mine water hydrology. Mine Water 2002:127–270.
[3] Bradley KF, Ashford KT. Application of geochemical mineral exploration techniques to the cataloguing of problematic discharges from abandoned mines in North-East England.
[4] Coldewey WG, Semrau L. Mine water in the Ruhr area (Federal Republic of Germany). In: Proceedings of 5th international mine water congress, September, vol. 9. Leicestershire: Quorn Selective Repro Limited; 1994. p. 148.
[5] Dumpleton S. The dangerous legacy of dead collieries. Int J Rock Mech Min Sci Geomech Abst 1996;1(33):41A.
[6] Younger PL. Hydrological consequences of the abandonment of regional mine dewatering schemes in the UK. In: Hydrology in a changing environment, July. Poster papers and index, international symposium organised by the British Hydrological Society; 1998. p. 6–10.
[7] Young PL. The longevity of minewater pollution: a basis for decision-making. Sci Total Environ 1997;194:457–66.
[8] Younger P. Possible environmental impact of the closure of two collieries in County Durham. Water Environ J 1993;7(5):521–31.
[9] Younger P. Coalfield abandonment: geochemical processes and hydrochemical products. Energy Environ. Geochem Fossil Nucl Renewa Resour. Soc Environ Geochem Health. MacGregor Sci 1998:1–29. Insch.
[10] Henton MP. The problem of water table rebound after mining activity and its effect on ground and surface water quality. Stud Environ Sci 1981;17:111–6.
[11] Gzyl G, Banks D. Verification of the “first flush” phenomenon in mine water from coal mines in the Upper Silesian Coal Basin, Poland. J Contam Hydrol 2007;92(1):66–86.
[12] Wood S, Younger P, Robins N. Long-term changes in the quality of polluted minewater discharges from abandoned underground coal workings in Scotland. Q J Eng Geol Hydrogeol 1999;32(1):69–79.
[13] Stoertz MW, Hughes ML, Wanner NS, Farley ME. Long-term water quality trends at a sealed, partially flooded underground mine. Environ Eng Geosci 2001;7(1):51–65.
[14] Henton M. Abandoned coalfields: problem of pollution. Survey 1979;153(9):e11.
[15] Banks D, Younger PL, Arnesen RT, Iversen ER, Banks SB. Mine-water chemistry: the good, the bad and the ugly. Environ Geol 1997;32(3):157–74.
[16] Neymeyer A, Williams R, Younger P. Migration of polluted mine water in a public supply aquifer. Q J Eng Geol Hydrogeol 2007;40(1):75–84.
[17] Younger PL. Towards regulatory criteria for discharging iron-rich mine water into the sea. Mine Water Environ 2008;27(1):56–61.
[18] Bailey MT, Gandy CJ, Watson IA, Wyatt LM, Jarvis AP. Heat recovery potential of mine water treatment systems in Great Britain. Int J Coal Geol 2016;164:77–84.
[19] Watzlaf GR, Ackman TE. Underground mine water for heating and cooling using geothermal heat pump systems. Mine Water Environ 2006;25(1):1–14.
[20] Hall A, Scott JA, Shang H. Geothermal energy recovery from underground mines. Renew Sustain Energy Rev 2011;15(2):916–24.
[21] Kindaichi S, Nishina D, Wen L, Kannaka T. Potential for using water reservoirs as heat sources in heat pump systems. Appl Therm Eng 2015;76:47–53.
[22] Raymond J, Therrien R. Low-temperature geothermal potential of the flooded Gaspé Mines, Québec, Canada. Geothermics 2008;37(2):189–210.
[23] Ramos EP, Breede K, Falcone G. Geothermal heat recovery from abandoned mines: a systematic review of projects implemented worldwide and a methodology for screening new projects. Environ Earth Sci 2015;73(11):6783–95.
[24] Digges La Touche G, Preene M. The potential use of ground energy in the mining industry–exploration to closure. In: Proceedings of the 11th international mine water association congress–mine water–managing the challenges; 2011. p. 161–6.
[25] Ghoreishi Madiseh SA, Ghomshei MM, Hassani FP, Abbasy F. Sustainable heat extraction from abandoned mine tunnels: a numerical model. J Renew Sustain Energy 2012;4(3):033102.
[26] Banks D, Skarphagen H, Wiltshire R, Jessop C. Heat pumps as a tool for energy recovery from mining wastes. Geol Soc, Lond, Spec Publ 2004;236(1):499–513.
[27] Farr G, Sadasivam S, Watson IA, Thomas HR, Tucker D. Low enthalpy heat recovery potential from coal mine discharges in the South Wales Coalfield. Int J Coal Geol 2016;164:92–103.
[28] Omer AM. Ground-source heat pumps systems and applications. Renew Sustain Energy Rev 2008;12(2):344–71.
[29] Self SJ, Reddy BV, Rosen MA. Geothermal heat pump systems: Status review and comparison with other heating options. Appl Energy 2013;101:341–8.
[30] Chua KJ, Chou SK, Yang WM. Advances in heat pump systems: a review. Appl Energy 2010;87(12):3611–24.
[31] Rodríguez R, Díaz MB. Analysis of the utilization of mine galleries as geothermal heat exchangers by means a semi-empirical prediction method. Renew Energy 2009;34(7):1716–25.
[32] Banks D, Skarphagen H, Wiltshire R, Jessop C. Mine water as a resource: space heating and cooling via use of heat pumps. Land Contam Reclam 2003;11(2):191–8.
[33] Al-Habaibeh A, Meyerowitz B, Athresh A. The design and development of an innovative simulator for an open loop system for extracting energy from flooded coal mines. Energy Proc 2015;75:1470–6.
[34] Nguyen HV, Law YLE, Alavy M, Walsh PR, Leong WH, Dworkin SB. An analysis of the factors affecting hybrid ground-source heat pump installation potential in North America. Appl Energy 2014;125:28–38.
[35] Jessop AM, MacDonald JK, Spence H. Clean energy from abandoned mines at Springhill, Nova Scotia. Energy Sour 1995;17(1):93–106.
[36] Jardón S, Ordóñez A, Alvarez R, Cienfuegos P, Loredo J. Mine water for energy and water supply in the Central Coal Basin of Asturias (Spain). Mine Water Environ 2013;32(2):139–51.
[37] Preene M, Younger PL. Can you take the heat?–Geothermal energy in mining. Min Technol 2014;123(2):107–18.
[38] Banks D, Pumar AF, Watson I. The operational performance of Scottish minewater-based ground source heat pump systems. Q J Eng Geol Hydrogeol 2009;42(3):347–57.
[39] Gillespie MR, Crane EJ, Barron HF. Deep geothermal energy potential in Scotland. British Geological Survey Commissioned Report, CR/12/131; 2013.
[40] Coal Authority UK. Coal Authority UK; 2016 < https://www.gov.uk/government/organisations/the-coal-authority > [accessed 05/05 2016].
[41] Parker K. Potential for heat pumps in Yorkshire and the rest of the United Kingdom. In: Faull ML, editor. Heat pump technology using minewater; 2011. p. 32–42.
[42] Burnside NM, Banks D, Boyce AJ, Athresh A. 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. Int J Coal Geol 2016;165:223–30.
[43] Athresh AP, Al-Habaibeh A, Parker K. The design and evaluation of an open loop ground source heat pump operating in an ochre-rich coal mine water environment. Int J Coal Geol 2016;164:69–76.
[44] Roijen E, Op‘t Veld P, Demollin-Schneiders E. The Minewaterproject Heerlen-low exergy heating and cooling in practice. In: PALENC AIVC; 2007.
[45] Verhoeven R, Willems E, Harcouët-Menou V, De Boever E, Hiddes L, Op't Veld P, Demollin E. 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 Proc 2014;46:58–67.
[46] Esen H, Esen M, Ozsolak Onur. Modelling and experimental performance analysis of solar-assisted ground source heat pump system. J Exp Theor Artif Intell 2017;29(1):1–17.
[47] Esen M, Balbay A. Experimental investigation of using ground source heat pump system for snow melting on pavements and bridge decks. Scient Res Essays 2010;5(24):3955–66.

[48] Balbay A, Esen M. Temperature distributions in pavement and bridge slabs heated by using vertical ground-source heat pump systems. Acta Scient-Technol 2013;35(4):677–85.

[49] Esen M, Yuksel T. Experimental evaluation of using various renewable energy sources for heating a greenhouse. Energy Build 2013;65:340–51.

[50] Athresh AP, Al-Habaibeh A, Parker K. Innovative approach for heating of buildings using water from a flooded coal mine through an open loop based single shaft GSHP system. Energy Proc 2015;75:1221–8.

[51] Banks D, Athresh A, Al-Habaibeh A, Burnside N. Water from abandoned mines as a heat source: practical experiences of open-and closed-loop strategies, United Kingdom. Sustain Water Resour Manage 2017:1–22.

[52] Athresh AP, Al-Habaibeh A, Parker K. An innovative and integrated approach for using energy from the flooded coal mines for pre-warming of a gas engine in standby mode using GSHP. Energy Proc 2017;105:2531–8.

[53] Ochsner K. Geothermal heat pumps: a guide for planning and Installing. Routledge; 2012.

[54] Bazargan Sabet D, Demollin E, Van Bergermeer J. Geothermal use of deep flooded mines. In: Proceedings of post-mining symposium. Nancy (France); 2008.

International Journal of Coal Geology 164 (2016) 69–76

Contents lists available at ScienceDirect

International Journal of Coal Geology

journal homepage: www.elsevier.com/locate/ijcoalgeo

The design and evaluation of an open loop ground source heat pump operating in an ochre-rich coal mine water environment

Anup P. Athresh [a], Amin Al-Habaibeh [a,*], Keith Parker [b]

[a] Innovative and Sustainable Built Environment Technologies Research Group (iSBET), Nottingham Trent University, NG1 4BU, UK
[b] Alkane Energy Plc, Edwinstowe House, Edwinstowe, Nottingham, NG21 9PR, UK

ARTICLE INFO

Article history:
Received 2 November 2015
Received in revised form 28 April 2016
Accepted 29 April 2016
Available online 30 April 2016

Keyword:
Sustainability
Green energy
Coal mines
Open loop GSHP
Mine water
Heat pump
Iron ochre
Condition based maintenance (CBM)

ABSTRACT

Mine water from the abandoned coal mines is considered a good source of low enthalpy energy resource as the temperature of the mine water remains stable throughout the year and is suitable to be used for heating and cooling applications when implemented in conjunction with Ground Source Heat Pump (GSHP). The GSHP is considered to be a low carbon technology and its application for space heating and cooling is being actively investigated and developed by companies and local councils around the world. The open loop GSHP installations, in comparison to closed loop systems, are suitable and economical for large scale heating and cooling demands. This is because there is no time delay for heat transfer when compared with closed loop systems and because they use large volumes of coal mine water at a relatively constant temperature. A few installations both large and small scale open loop mine water heating and cooling systems have been recently constructed throughout the world. However, coal mine water is associated with relatively poor water quality in some cases, often characterised by high salinity and pyrite oxidation. Despite the fact that mine water temperatures are favourably inclined for an efficient GSHP operations, concerns have been raised over the possibility of damage to the equipment due to poor water quality caused by clogging of the heat exchangers due to pyrite oxidation (ochre) in particular. Not much information is available on the impact of ochre has on the performance of an open loop GSHP when it is operated using the coal mine water rich in pyrite. This paper presents a novel design and implementation of an open loop system of GSHP operating in an ochre rich mine water environment. The results show that open loop systems, when combined with suitable heat pump and the associated design configurations of heat exchangers and maintenance procedures, could provide an efficient and reliable heating system at a lower cost.

1. Introduction

The National Coal Mining Museum (NCM) for England, see Fig. 1, is on the site of former Caphouse Colliery which is located in Overton, near Wakefield, Yorkshire in the UK at 53.6416° N 1.6251° W with site elevation of about + 147 m asl. As shown in Fig. 1, the Caphouse Colliery complex is underlain by Lower Coal Measures in the west and the Middle Coal Measures in the east. The strata consist of cyclical fluvio-deltaic sequences of interbedded sandstone, siltstone, mudstones, coal and associated seatearth, the regional geology dips at an average angle of 3–5° in south west direction (INWATCO, 2005a; Burnside et al., 2016). Caphouse Colliery complex was interconnected to other collieries in the area including the Denby Grange Colliery (53.6340° N 1.5942° W) and Woolley Colliery (53.5961° N 1.5338° W), see for example INWATCO (2005a) and INWATCO (2005b). The Flockton Thick, Flockton Thin, First Brown Metal, Old Hards, Third Brown Metal, Green Lane, New Hards, Wheatley Lime/Old Man, Blocking and Beeston coal seams have been exploited at the Caphouse Colliery complex (Brown and Goodchild, 1979; Wilcockson, 1950). The coal mines in this region of Yorkshire and Nottinghamshire has an average sulphur content of about 2.13% (Spears and Tewalt, 2009). The Caphouse Colliery was sunk in the year 1780 (Faull, 2011) and the Hope pit was opened in 1830 (Schofield, 2003; Goodchild, 1983). The Colliery complex was closed in 1985 and the museum was opened in 1988 where the underground galleries were opened to public. In order to keep the underground galleries dry and safe, the water was pumped from the pit and discharged into river Calder, the pumping continued till 1993. The pumping of water of the resumed in the year 1996, when the water level started to rise due to a loss of hydraulic connectivity (perhaps due to a collapse of a road way) with neighbouring Woolley shaft (Faull, 2011).

Mine water in abandoned coal mines, such as Caphouse Colliery, can be considered as a good source of low grade geothermal energy, owing to their stable temperature throughout the year and huge volumes of water which are contained in the underground voids and interconnected roadways stretching long distances. The temperatures of the mine water at a depth of 100 m in UK is circa 13–14 °C (Banks et al., 2004). For air conditioning applications coal mine water could be used directly. However, this level of temperature can be considered

* Corresponding author.
E-mail address: Amin.Al-Habaibeh@ntu.ac.uk (A. Al-Habaibeh).

http://dx.doi.org/10.1016/j.coal.2016.04.015
0166-5162/

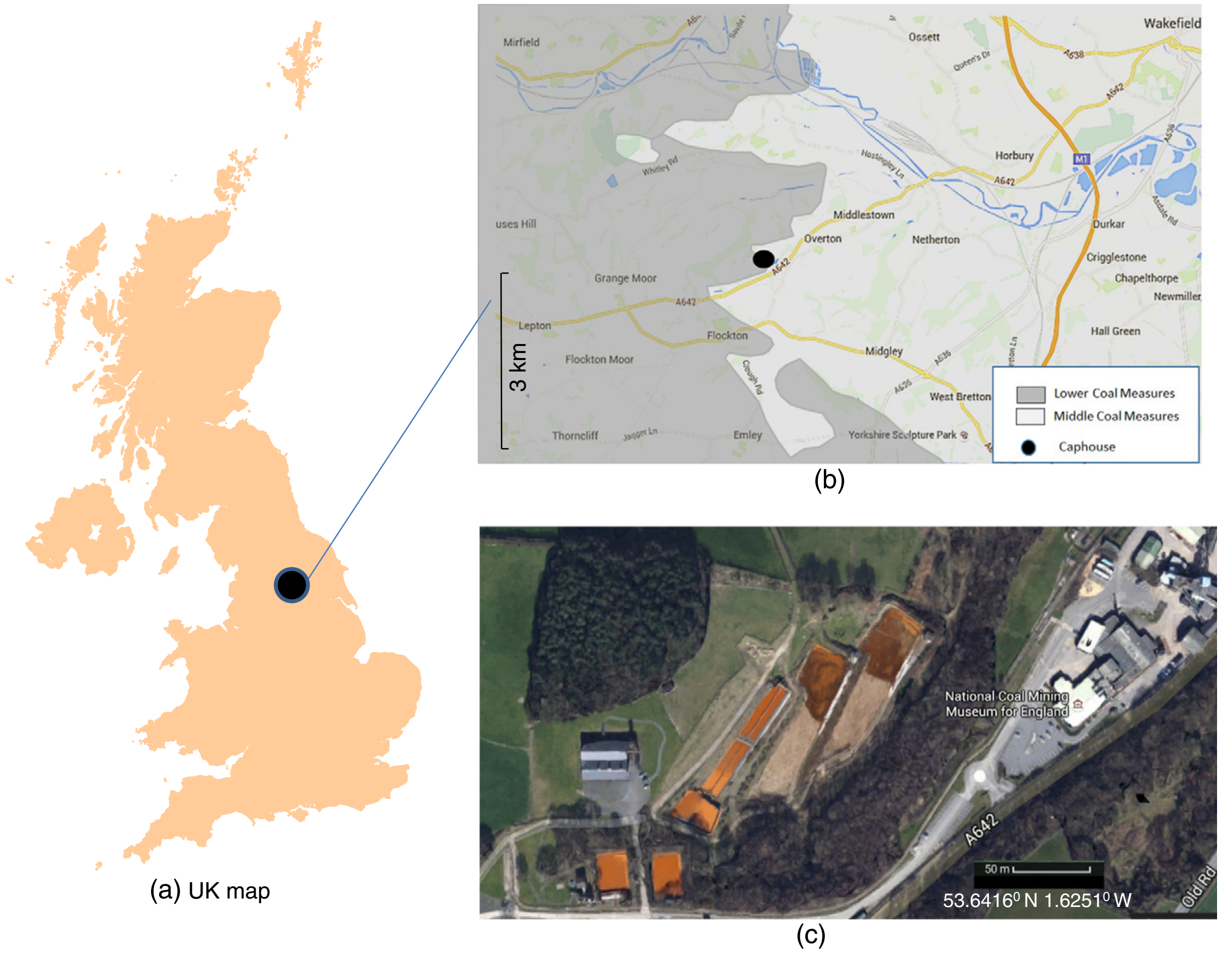


Fig. 1. UK map indicating the location of Caphouse Colliery (a), Caphouse Colliery coal measures map completed using BGS bedrock geology (1:625,000) and Google map (b) and a satellite image where the current mine water treatment lagoons appear in orange colour (source: Google Earth) (c).

too low to be used directly for heating applications. To achieve this, the use of heat pumps enables the temperature to be upgraded for space heating, allowing the temperature to reach low to mid 50 °C. The heat pump converts the low grade energy into a high grade energy. The majority of the abandoned coal mines lie close to or within former mining towns and villages which are now being developed as industrial

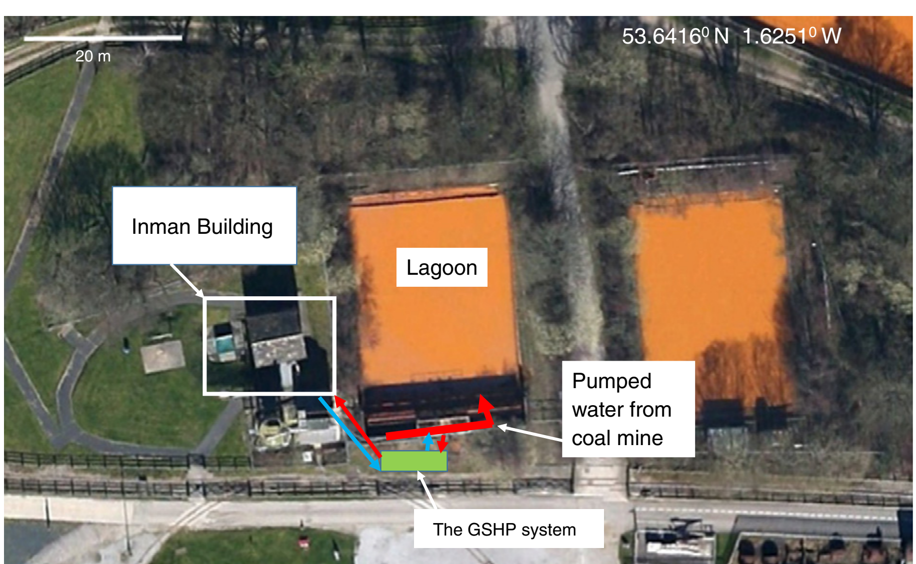


Fig. 2. A Google satellite image of the location with a schematic diagram of the implementation of the system.

Fig. 3. Main components of the system, Inman shaft building heated by the heat pump (a), the lagoon (b), plant housing container (c) and the container with the main two pipes that pump the water from the coal mine (d).

buildings or residential housing, creating large heating and cooling needs with the possibility of the implementation of district heating networks. The potential of the coal mine water as a sustainable source of energy for space heating and cooling is enormous, however, till 2013 <20 installations were documented (Preene and Younger, 2014).

A detailed theoretical description of the heat pump regarding the working, types and configuration has been mentioned in Athresh et al. (2015), Banks et al. (2004), Omer (2008), Watzlaf and Ackman (2006) and Banks (2012). Al-Habaibeh et al. (2015) have identified the need for technology training and have developed a novel simulator for teaching the technology. The recent advances in the heat pump technology have been described in detail in Chua et al. (2010). The models to estimate the amount of thermal energy that can be recovered of mine water in the underground galleries has been described by several authors including Rodríguez and Díaz (2009), Madiseh et al. (2012), and Andrés et al. (2015). The details of mine water based heating and cooling installations throughout the world has been described by Hall et al. (2011), Ramos et al. (2015) and Preene and Younger (2014). A successful small scale heating system in Markham Vale in the UK has been described by Athresh et al. (2015). A pilot mine water heating and cooling scheme has been successfully implemented in the Dutch town of Herleen and the details of this scheme has been described in Roijen

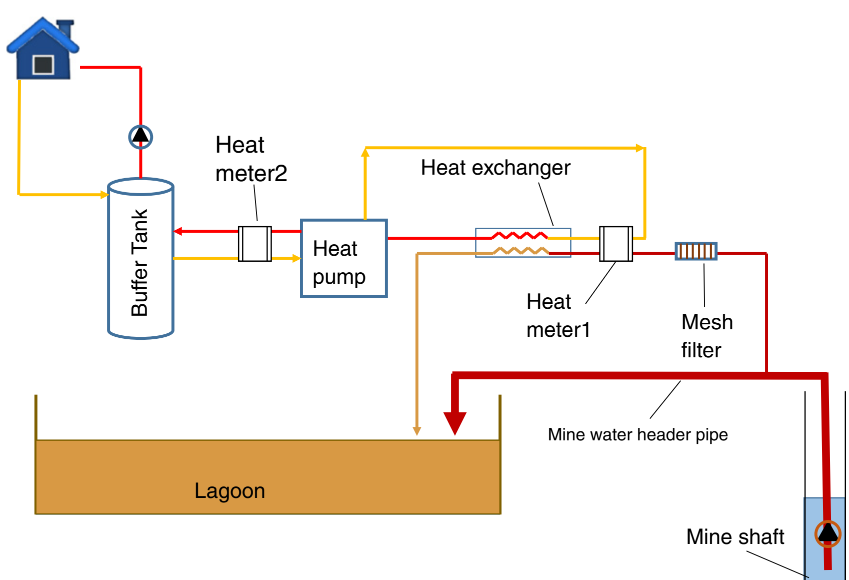


Fig. 4. A simplified schematic diagram of the system.

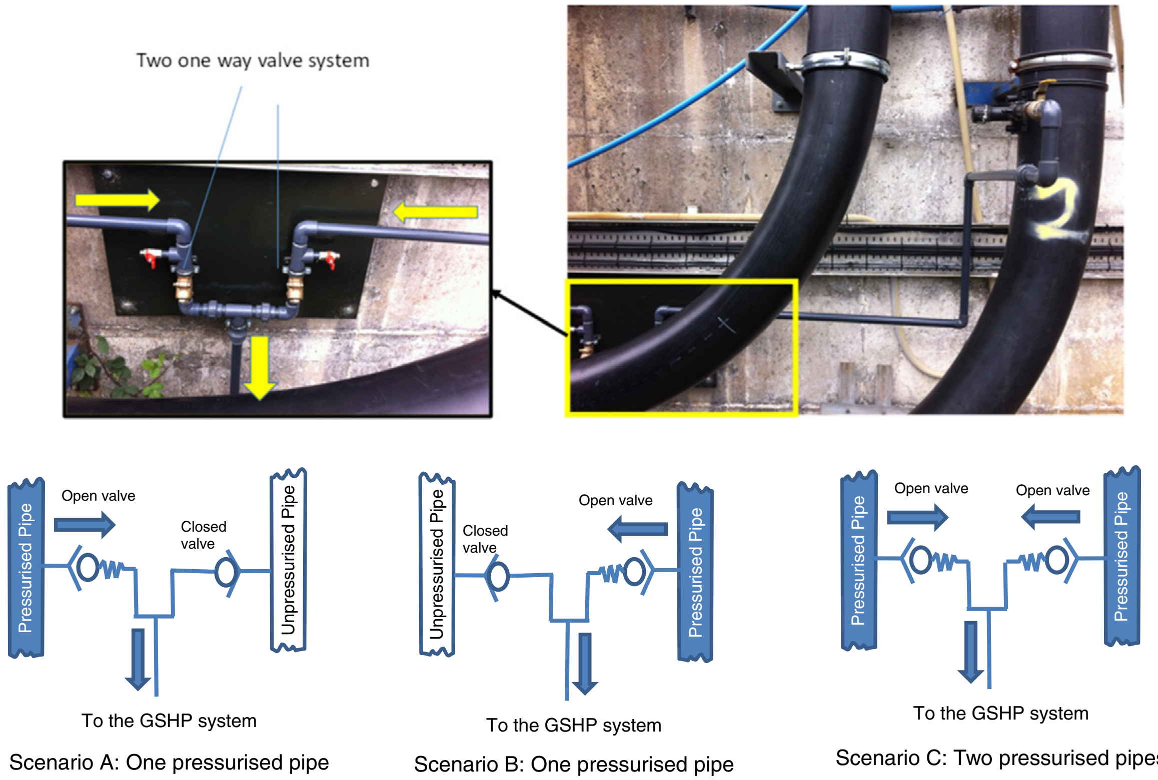


Fig. 5. A novel design of one way valve system allows the GSHP to operate effectively from either pipe when pressurised without losing the pressure to the other unpressurised pipe.

et al. (2007). Following the success of the pilot scheme, the scheme was upgraded to a full scale sustainable energy system and this has been documented in Verhoeven et al. (2014). The scheme at Herleen requires a special mention as it shows how a former mining town facing a social and economic crisis following the closure of the mines has successfully managed to transform itself using the mine water heating and cooling scheme to a sustainable town. Herleen project has shown the way forward to other mining towns around the world still struggling with lack of energy resources and closure of mines.

The open loop based GSHP systems perform much better than closed loop systems when there is a large energy demand requirements, as it eliminates the time needed for heat transfer to take place between the

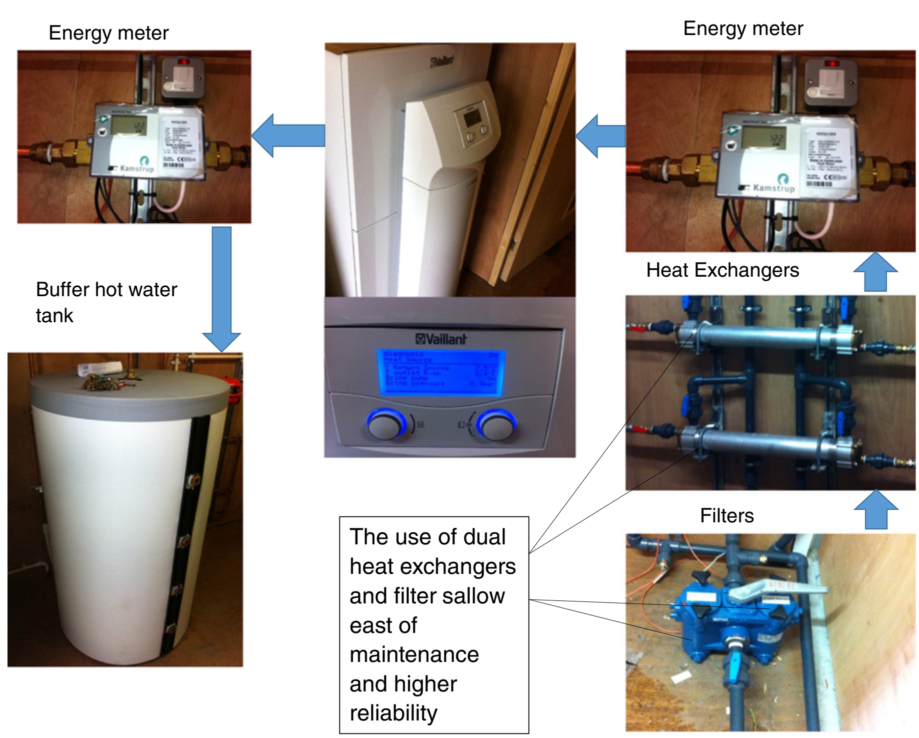


Fig. 6. The main components of the GSHP system.

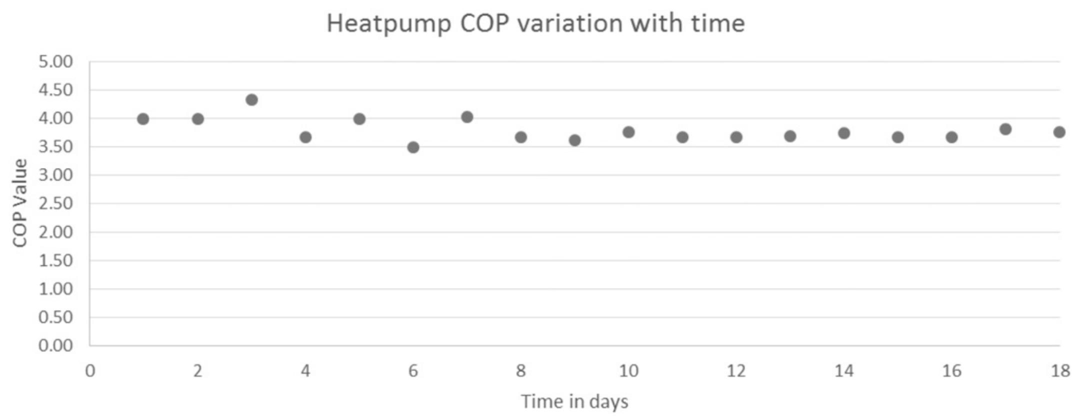


Fig. 7. The COP of the system during the testing process for 18 days.

fluid in the closed loop and the external environment. However in open loop systems, the equipment will be exposed directly to the minerals in the mine water and this increases the possibility of a potential damage to the equipment, especially when the system is installed in an ochre rich environment (Banks et al., 2009). Currently limited research has been done in relation to the design and implementation of such systems in ochre rich water systems, particularly the impact of ochre clogging on the equipment and the performance of the system. By means of pilot plant this research work aims to characterise the performance of the system and also find a suitable maintenance regime to overcome this problem.

This paper presents a system that uses a prophylactic shell and tube heat exchanger to prevent the mine water from coming in direct contact with the heat pump. This is done by transferring the thermal energy from the mine water to an intermediary brine solution in the heat exchanger. A shell and tube heat exchanger is employed instead of the more common plate heat exchanger, as it is easier to clean for maintenance applications. In addition, a novel implementation of alternating use of two heat exchangers and filters, i.e. a second heat exchanger and a filter will always be on standby if maintenance is needed, thereby guaranteeing a continuous operation of the whole system.

2. The implemented GSHP system location

Caphouse colliery, where the system has been implemented, is now a part of the National Coal mining museum for England (NCM, 2015), where part of the underground galleries have now been converted into a museum and is open to the public. The underground galleries has to be kept dry and safe for the visiting public and for this reason dewatering pumps are employed to pump out the water. Unfortunately, the energy from this relatively warm water was not utilised efficiently despite the need for significant heating demands for the buildings of the museum. The mine water in that location has an iron content of circa 15 mg/l (Burnside et al., 2016) and is partially oxidised in the pumping shaft. The pumped water is ochre rich and undergoes passive treatment using several settling tanks and reed beds to remove the ochre before discharging it into a water stream. Fig. 1 presents a Google satellite image of the water treatment tanks where the orange colour due to ochre is clearly visible.

3. Plant description

The implemented GSHP system consists of a single 10.5 kW commercial Vaillant heat pump, two sets of prophylactic shell and tube type heat exchangers. The two heat exchangers are implemented in alternating way during operation to allow for maintenance where one will always be on standby. A mesh filter is also used to provide initial filtration before the heat pump. The filter unit also includes two alternating separate filters to allow easy maintenance similar to the heat exchanges. A 300 l buffer tank is used to allow stable operation of the heat pump during fluctuation in heating demands. The heat from the system is used for heating the old Inman shaft building which is

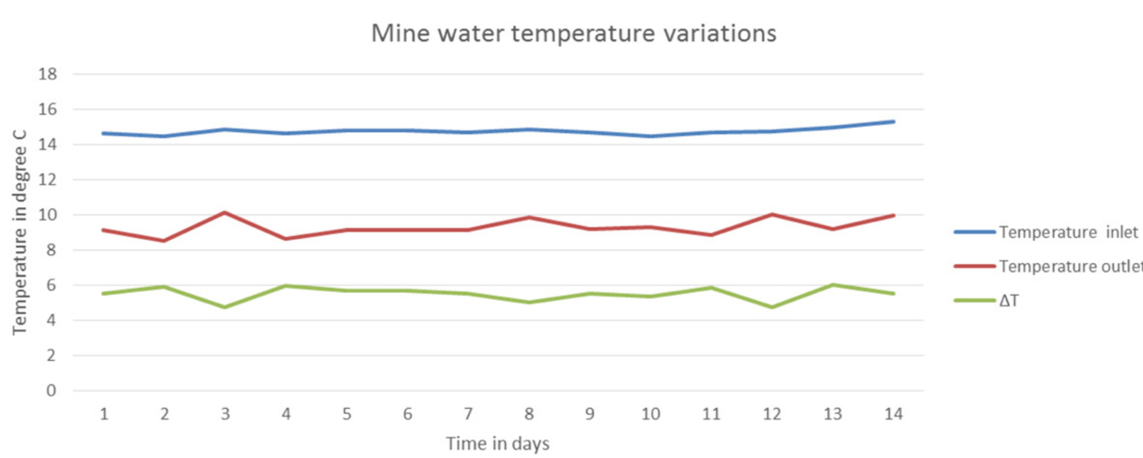


Fig. 8. The variation of mine water temperature parameters.

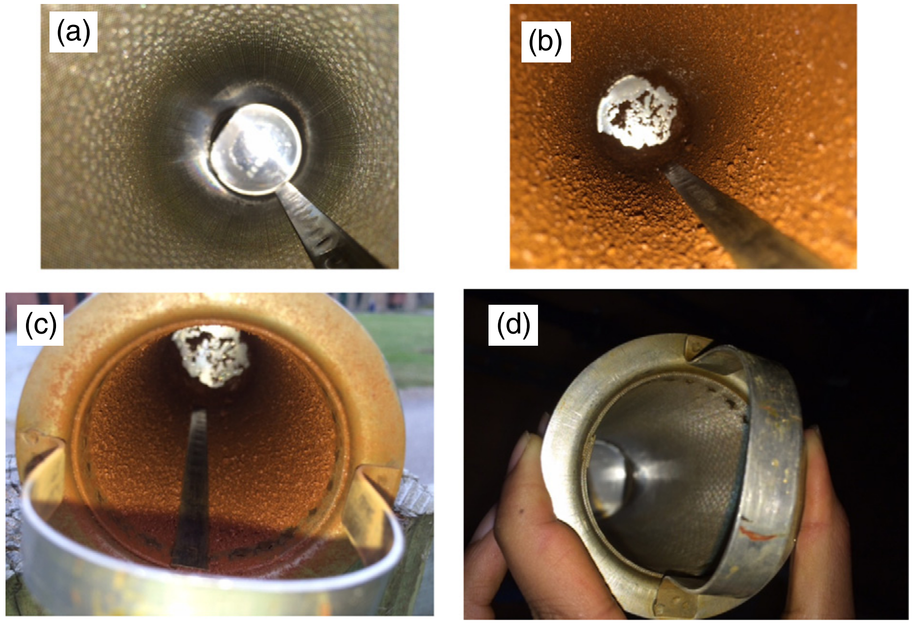


Fig. 9. The conditions of the filter as new (a), after several days of operation (b, c) and after cleaning (d).

currently used as an exhibition space at the museum. In order to keep the mining museum galleries dry, water needs to be pumped daily, at a flow rate of circa 30 l/s. During the winter months, water is pumped 24 h a day and in summer months the water is pumped for circa 15 h a day. A small amount of mine water is tapped from the main pumping header line and used in the pilot plant and later injected back to the mine water treatment lagoon. Fig. 2 presents a satellite image of the location and a schematic diagram of the pilot plant system. Fig. 3 presents further details of the components of the system, where Fig. 3-a presents the Inman building, Fig. 3-b presents the first lagoon where the water from the coal mine is first exhausted to, Fig. 3-c presents the location of the container that includes the system and Fig. 3-d presents part of the container and the main two header pipes through which the mine water is pumped to the treatment lagoons.

When considering the structure of the system, Fig. 4 presents a schematic diagram of the system. As described, the water is pumped from the coal mine to prevent flooding. The water is transferred to lagoons where it is treated by allowing the suspended iron oxide to precipitate, hence cleaning the water for the local water streams. The system tap into the header pipes without the need for an additional pump and the water is circulated via mesh filtering before passing to the heat exchanger and released to the lagoon. A heat pump is used to extract the energy through an isolated system using the heat exchanger and then the extracted heat is used to heat the water in a hot water buffer tank. The rest of the system works as a classical heating system where the hot water in the buffer tank is pumped via an additional standard water pump to the building. Standard radiators are used for the purpose of heating the building.

The system for pumping water from the coal mine includes two parallel systems (header pipes) one or both could be operating at any specific time. To allow the extraction of water by either pipe, a novel design (see Fig. 5) allows the heating system to circulate water from either pipe based on their pressure, and at the same time preventing the loss of pressure due to water leakage to the low pressure/empty one. If both systems are pressurised, this will create a functional flow based on the lowest pressure assuming both are above the threshold value of the valves.

4. Data acquisition and monitoring of the system

The main parameters which need to be monitored to determine the performance of the system (see next section) are energy consumption and heat transfer rates between the mine water and the brine. These

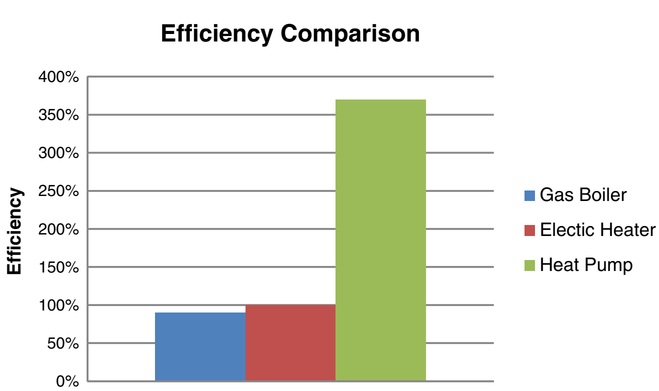


Fig. 10. Efficiency comparison using gas, electricity and heat pump heating systems.

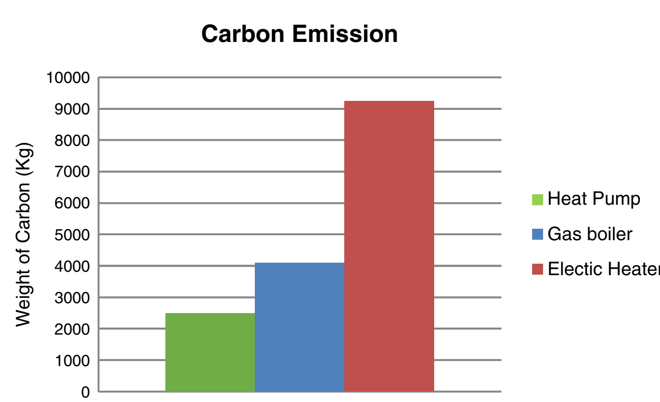


Fig. 11. Comparison between carbon emission of the suggested heat pump system in comparison to a gas boiler and an electric heater.

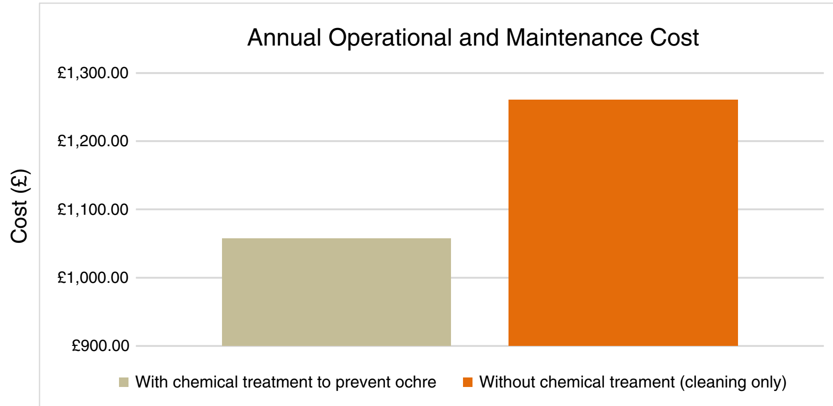


Fig. 12. Operational and maintenance cost of the heat pump using two different maintenance schemes.

are determined by measuring the fluid input and output temperatures and instantaneous flow rates. Two Kamstraup heat meters are used to monitor both the mine water and heat pump output parameters. The heat meter measures the flow rate in m^3/h, ΔT of water, instantaneous energy in kWh and cumulative energy in MWh. The Kamstraup heat meter consists of an integrated flow and temperature sensors and an integrator to calculate the energy based on the flow and temperature values. The entire monitoring system is coupled to telemetry and the data is continuously collected. Fig. 6 presents images of the main components of the system. The arrows indicate the stages of energy or water flow between components.

5. Main performance indicators

The efficiency of a Heat pump is measured in terms of COP (Coefficient of Performance). It is the main parameter of interest. It is the ratio between the thermal energy output of the heat pump and the electrical energy consumed by the heat pump. The amount of energy produced and consumed by the heat pump mainly depends upon the heat transfers between the mine water and brine, brine and evaporator of the heat pump and between the condenser of the heat pump and building heating fluid. The COP of the system is normally measured by the thermal output of the system relative to the energy consumed by the system. This is, in addition to the heat pump itself, includes the pumping of water from the coal mine and the pumping of water to the end user radiators via the circulation pump. In this application, since the water is pumped as part of the original system and the circulation pump power is negligible when compared with the heat pump, the COP of the heat pump is almost identical to the COP of the system.

In mathematical terms:

$$COP_{Heatpump} = \frac{\text{Thermal energy produced}}{\text{Electrical energy consumed}} \quad (1)$$

$$COP_{system} = \frac{\text{Thermal energy produced by system}}{\text{Electrical energy consumed by system}}. \quad (2)$$

In this case:

$$COP_{heatpump} \approx COP_{system} \quad (3)$$

6. Results and discussion

6.1. COP and temperatures

The presented data has been collected during the operation of the heat pump during summer time of 2015. Fig. 7 presents the efficiency (COP) of the heat pump which varies between 3.5 and 4.5 depending on the heating demand which is related to the environmental conditions. The efficiency is slightly lower than expected as this data was collected during summer when the demand for heat is the least. When the heat pump operates under part load conditions, the cycling of the compressor (i.e. frequent on and off) of the heat pump takes place and leads to the reduction in efficiency. Fig. 8 presents the water temperature from the coal mine and the water exiting the heat exchanger. The mine water seems to be stable at about 14.5 °C, hence indicating a reliable source of low enthalpy energy.

6.2. Maintenance and reliability issues

In relation to maintenance issues, due to the quality of water, Fig. 9 presents the filtering system following several days of operation using the water without any treatment. There is a clear ochre occurrence on the filters that could cause blockages. However, the alternating between the two filters allowed the cleaning process to take place while the system in full operation.

6.3. Cost and performance

For a peak thermal output of 10 kW, 2000 h of operation and an annual heating demand of 20 MWh, Figs. 10 and 11 present the efficiency of the system and the carbon emission respectively. It is clear that the GSHP has a much higher efficiency due to the energy extracted from coal mine water. Also it has much improved carbon emission as a result of that.

Fig. 12 presents the annual operational and maintenance cost of the heat pump. It is estimated that the electricity consumption cost will be about £540.54 and the maintenance cost will be about £517 per annum for the chemical treatment of water to prevent ochre. The mechanical cleaning process of filters (manual cleaning) will cost about £720 per annum. This is indicating a difference of about £200 between the two schemes. However, the chemical treatment can be automated which might be easier to manage on the long term.

7. Conclusion and future work

This paper has presented a novel design and implementation of open loop Ground Source Heat Pump operating in an ochre rich mine water environment. The system has been implemented at the UK's National Coal Mining Museum. Despite the poor quality of water, this system has been implemented successfully using dual filters and dual heat exchanger system which will allow ease of maintenance and guarantee continuous operation of the system. The advantage of the GSHP in this particular location, in addition to increasing efficiency and reducing carbon emission, is educating the visitors of the museum regarding this technology which will allow public engagement for enhancing the future of this technology within the public domain.

Future work will involve the monitoring of the GSHP system over a two year period for full evaluation. Future work would involve studying the impact ochre deposition has on the overall efficiency of the system, developing a dynamic GSHP system model for optimising the GSHP parameters and creating a condition based maintenance strategy for using a GSHP system in an ochre prone environment.

Acknowledgment

The authors would like to thank the National Coal Mining Museum for supporting this research work. This paper is based on field research carried out within the frame of research project: Low-Carbon After-Life (LoCAL) financed by the European Commission, Research Fund for Coal and Steel, July 2014–June 2017 (Contract No.: RFCR-CT-2014-00001).

References

Athresh, A., Al-Habaibeh, A., 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. Energy Procedia 75, 1221–1228.

Al-Habaibeh, A., Meyerowitz, B., Duolan, Athresh, A., 2015. The design and development of an innovative simulator for an open loop system for extracting energy from flooded coal mines. Energy Procedia 75, 1470–1476.

Andrés, C., Ordóñez, A., Álvarez, R., 2015. Hydraulic and thermal modelling of an underground mining reservoir. Mine Water Environ. 1–10.

Banks, D., Pumar, A.F., Watson, I., 2009. The operational performance of Scottish minewater-based ground source heat pump systems. Q. J. Eng. Geol. Hydrogeol. 42 (3), 347–357.

Banks, D., 2012. An Introduction to Thermogeology: Ground Source Heating and Cooling. John Wiley & Sons.

Banks, D., Skarphagen, H., Wiltshire, R., Jessop, C., 2004. Heat pumps as a tool for energy recovery from mining wastes. Geol. Soc. Lond., Spec. Publ. 236 (1), 499–513.

Chua, K., Chou, S., Yang, W., 2010. Advances in heat pump systems: A review. Appl. Energy 87 (12), 3611–3624.

Faull, M.L., 2011. Plans for an open-loop heat-pump system at the National Coal Mining Museum for England. National Coal Mining Museum for England Special Publications v.13, Heat-pump Technology Using Minewater, pp. 43–48.

Hall, A., Scott, J.A., Shang, H., 2011. Geothermal energy recovery from underground mines. Renew. Sust. Energ. Rev. 15 (2), 916–924.

INWATCO, 2005a. Integrated Water Management in Former Coal Mining Regions: Guidance to Support Strategic Planning. Report http://www.wise-rtd.info/sites/default/files/d-2007-07-03-good_practice_guide.pdf.

INWATCO, 2005b. Integrated Water Management in Former Coal Mining Regions: Non-technical Summary. (Report) http://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=home.showFile&rep=file&fil=LIFE02_ENV_UK_000140_LAYMAN.pdf.

Brown, I., Goodchild, J., 1979. The coal mines of the Flockton area, near Horbur, West Yorkshire. Bull. Peak Dist. Min. Hist. Soc. 7 (3), 169–173.

Goodchild, J., 1983. Caphouse Colliery and the Denby Grange Collieries. 13 ed. Wakefield Historical Publications, Wakefield.

Madiseh, S.G., Ghomshei, M.M., Hassani, F., Abbasy, F., 2012. Sustainable heat extraction from abandoned mine tunnels: a numerical model. J. Renewable Sustainable Energy 4 (3), 033102.

NCM, 2015. National Coal Mining Museum website https://www.ncm.org.uk (accessed on 15 October 2015).

Burnside, N.M., Banks, D., Boyce, A.J., 2016. Sustainability of thermal energy production at the flooded mine workings of the former Caphouse Colliery, Yorkshire, United Kingdom. Int. J. Coal Geol. 164, 84–90

Omer, A.M., 2008. Ground-source heat pumps systems and applications. Renew. Sust. Energ. Rev. 12 (2), 344–371.

Preene, M., Younger, P., 2014. Can you take the heat?—geothermal energy in mining. Min. Technol. 123 (2), 107–118.

Ramos, E.P., Breede, K., Falcone, G., 2015. Geothermal heat recovery from abandoned mines: a systematic review of projects implemented worldwide and a methodology for screening new projects. Environ. Earth Sci. 73 (11), 6783–6795.

Rodríguez, R., Díaz, M.B., 2009. Analysis of the utilization of mine galleries as geothermal heat exchangers by means a semi-empirical prediction method. Renew. Energy 34 (7), 1716–1725.

Roijen, E., P., Op't Veld, Demollin-Schneiders, E., 2007. The mine water project Heerlen-low energy heating and cooling in practice. PALENC AIVC.

Schofield, J., 2003. Caphouse Colliery; a Brief Mining History. third ed. (Overton).

Spears, D.A., Tewalt, S.J., 2009. The geochemistry of environmentally important trace elements in UK coals, with special reference to the Parkgate coal in the Yorkshire–Nottinghamshire Coalfield, UK. Int. J. Coal Geol. 80 (3), 157–166.

Verhoeven, R., Willems, E., Harcouët-Menou, V., de Boever, E., Hiddes, L., P., Op't Veld, 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.

Watzlaf, G.R., Ackman, T.E., 2006. Underground mine water for heating and cooling using geothermal heat pump systems. Mine Water Environ. 25 (1), 1–14.

Wilcockson, W.H., 1950. Sections of Strata of the Coal Measures of Yorkshire. third ed. Midland Institute of Mining Engineers, Sheffield.

Sustain. Water Resour. Manag.
DOI 10.1007/s40899-017-0094-7

ORIGINAL ARTICLE

Water from abandoned mines as a heat source: practical experiences of open- and closed-loop strategies, United Kingdom

David Banks[1,2] · Anup Athresh[3,4] · Amin Al-Habaibeh[3] · Neil Burnside[1]

Received: 31 August 2016 / Accepted: 15 February 2017

Abstract Pilot heat pump systems have been installed at two former collieries in Yorkshire/Derbyshire, England, to extract heat from mine water. The installations represent three fundamental configurations of heat exchanger. At Caphouse Colliery, mine water is pumped through a heat exchanger coupled to a heat pump and then discharged to waste (an open-loop heat exchange system). The system performs with high thermal efficiency, but the drawbacks are: (1) it can only be operated when mine water is being actively pumped from the colliery shaft for the purposes of regional water-level management, and (2) the fact that the water is partially oxygenated means that iron oxyhydroxide precipitation occurs, necessitating regular removal of filters for cleaning. At Markham Colliery, near Bolsover, a small amount of mine water is pumped from depth in a flooded shaft, circulated through a heat exchanger coupled to a heat pump and then returned to the same mine shaft at a slightly different depth (a standing column arrangement). This system's fundamental thermal efficiency is negatively impacted by the electrical power required to run the shaft submersible pump, but clogging issues are not significant. In the third system, at Caphouse, a heat exchanger is submerged in a mine water treatment pond (a closed-loop system). This can be run at any time, irrespective of mine pumping regime, and being a closed-loop system, is not susceptible to clogging issues.

Keywords Heat pump · Colliery · Mine water · Green energy · Thermogeology · Iron

Introduction: mine water as a thermal resource

In active mines, inflowing mine water needs to be removed from the mine system to allow working. This is often achieved in shallow mines by gravity drainage via soughs or adits to nearby valleys or watercourses. In deep mines, active pumping is required. The groundwater removed from the mine is at or somewhat above the annual average soil temperature of the locality in question and increases with depth (1–3 °C per 100 m in most tectonically stable areas: Banks 2012). Air must also be circulated carefully through the workings: in winter, the cold downdraught air acquires heat from the rocks as it circulates through the network of tunnels, and the return air is thus warm and can be used for pre-warming machinery or space heating systems.

When a mine is abandoned, one of three hydrological fates typically awaits the mine system:

1. the pumps are switched off and the mine gradually fills with groundwater until it overflows at the surface via a shaft top, an unplugged exploration borehole, a sough, tunnel or adit.
2. the mine continues to be pumped to prevent it filling with water and threatening other working mines down-dip (Janson et al. 2009).

This article is part of the special issue on Sustainable Resource Management: Water Practice Issues.

✉ David Banks
david@holymoor.co.uk

[1] School of Engineering, James Watt Building (South), University of Glasgow, Glasgow G12 8QQ, UK

[2] Holymoor Consultancy Ltd., 360 Ashgate Road, Chesterfield, Derbyshire S40 4BW, UK

[3] Innovative and Sustainable Built Environment Technologies Research Group (iSBET), Nottingham Trent University, Nottingham NG1 4BU, UK

[4] Alkane Energy Plc, Edwinstowe House, Edwinstowe, Nottingham NG21 9PR, UK

Published online: 13 April 2017

3. the mine, or interconnected mine system, continues to be pumped at one locality (or a limited number of localities) in order to prevent uncontrolled outbreaks of water at the surface (Banks et al. 1997a)

Many (but not all) coal, oil shale and metal deposits contain a significant content of sulphide minerals, such as pyrite (FeS_2). When exposed to circulating water and oxygen (as is the case in a working mine), these oxidise to form either metal-rich solutions of sulphuric acid, or secondary acidic metal sulphate minerals. These minerals, which may include phases such as jarosite $(K,Na,H)Fe^{III}{}_3(OH)_6(SO_4)_2$, melanterite ($FeSO_4.7H_2O$), römerite ($Fe^{II}Fe_2{}^{III}(SO_4)_4.14H_2O$) or copiapite ($Fe^{II}Fe^{III}{}_4(SO_4)_6(OH)_2.20H_2O$), represent a "store" of acidity, metals and sulphate, which can be released into solution when exposed to water, for example, when the mine floods (Bayless and Olyphant 1993; Younger 2000). Thus, the water initially overflowing from abandoned mines is typically rich in dissolved metals (especially iron), sulphate and can be acidic (Banks et al. 1997a, b). These concentrations will often decline with time as the secondary oxidation products are consumed by dissolution (Gzyl and Banks 2007; see also Burrows et al. 2015). Dold (2017) provides a recent thorough review of mineral acidity generating potential. Neglecting the intermediate (secondary mineral) steps, the overall reaction (for pyrite) can be represented by the, admittedly simplified, Eq. (1):

$$2FeS_2 + 7O_2 + 2H_2O = 2Fe^{2+} + 4SO_4{}^{2-} + 4H^+{}_{(aq)} \quad (1)$$

Following this reaction, the acid may be neutralised by reaction with carbonate or silicate minerals in the host rocks:

$$2Fe^{2+} + 4SO_4{}^{2-} + 4H^+{}_{(aq)} + 4CaCO_3 = 2Fe^{2+} + 4SO_4{}^{2-} + 4Ca^{2+} + 4HCO_3{}^- \quad (2)$$

Thus, many neutralised mine waters are relatively rich in base cations and bicarbonate alkalinity. In the Coal Measures rocks of the UK, iron-bearing carbonates such as siderite ($FeCO_3$) and ankerite ($Ca(Fe,Mg,Mn)(CO_3)_2$) can occur (Crook 1912; Hawkes and Smythe 1935; Eden et al. 1957; Lake and Hough 2006), such that this neutralisation reaction can release yet more ferrous iron to solution. If exposed to oxygen, the iron released by Eq. (1) or by iron carbonate dissolution can oxidise to form ferric iron, which is insoluble at all but very low pH values, precipitating as flocs of iron (III) hydroxide:

$$4Fe^{2+} + O_2 + 4H^+{}_{(aq)} + 10H_2O = 4Fe^{3+} + 12H_2O = 4Fe(OH)_3 + 12H^+{}_{(aq)} \quad (3)$$

The various steps in Eq. (3) are temperature dependent, but experimentation strongly indicates that an increase in temperature (at least in the range 0–35 °C) tends to increase the rate of iron oxidation and hydroxide precipitation (Faraldo Sanchez 2007; Raftery 2016).

This ferric (oxy)hydroxide typically imparts an orange coloration to watercourses receiving mine drainage and is commonly known in the mining industry as "ochre" or "yellowboy" or, in stricter mineralogical parlance, limonite. With time, the ferric hydroxide progressively loses water, crystallises and hardens (Grundl and Delwiche 1993). Thus, the terms "ochre" or limonite are non-mineralogically specific and are used to describe a mixture of hydrated iron oxides that may range from amorphous ferric hydroxide ($Fe(OH)_3$), through ferrihydrite (metastable nanocrystalline $Fe_2O_3\cdot(H_2O)_n$, where $n=1.8$–0.5) and goethite ($FeOOH$) to haematite (Fe_2O_3). For convenience, we will henceforth use the term "ochre" in this article. The ochre settling out on the beds of these watercourses can also smother the benthic fauna that fish feed on, negatively impacting the ecology of the watercourse. Mine waters, their acidity, salt and metal loadings and the ochre issues that follow are typically regarded as an environmental liability. The UK Coal Authority expends considerable effort and financial resources in managing this liability, both in terms of regional pumping of interconnected mine workings, to control mine water levels, and in treating pumped and gravity discharges of mine water (Banks and Banks 2001).

However, these mine water discharges can be viewed as a "green" renewable energy asset. Their temperature renders them suitable for space heating (via the use of heat pump technology) in the winter and as a heat sink for space cooling in the summer. The enormous volumes of mine workings and highly transmissive nature of mine roadways imply that the thermal storage associated with such workings is substantial and that very large water yields (several tens or even hundreds of $L\ s^{-1}$) can be abstracted from open flooded roadways and shafts. Simply by extracting a few °C of heat from a flow of, say, 50 $L\ s^{-1}$ of mine water can result in MW-scale quantities of thermal potential:

$$\text{Heat power available} = Q \cdot \Delta T \cdot \rho_w \cdot c_w \quad (4)$$

$$\text{Example:} 50\ L\ s^{-1} \times 4\ °C \times 4190\ J\ L^{-1} °C^{-1} = 838{,}000\ J\ s^{-1} = 0.838\ MW,$$

where Q = mine water flow in $L\ s^{-1}$ (say, 50 $L\ s^{-1}$), ΔT = temperature change at heat exchanger in °C (say, 4 °C), ρ_w = density ($kg\ L^{-1}$) and c_w = specific heat capacity ($J\ kg^{-1}\ °C^{-1}$) of water and hence, $\rho_w \times c_w$ = volumetric heat capacity of water ($J\ L^{-1}\ °C^{-1}$) = c. 4190 $J\ L^{-1}\ °C^{-1}$.

Such mine water-based heating schemes have been operational at a number of locations globally for

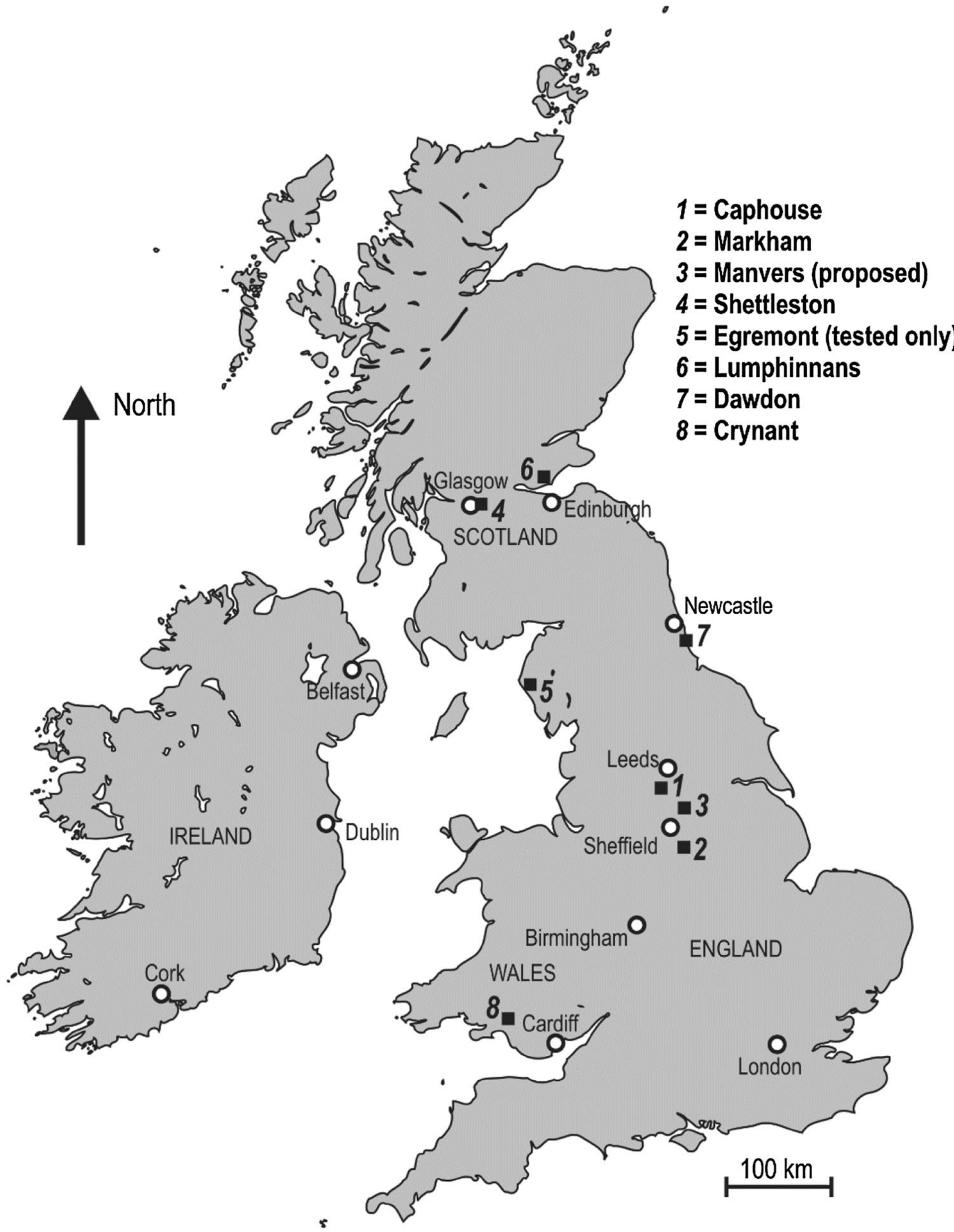


Fig. 1 Overview map of Britain and Ireland, showing mine water heat pump schemes. Egremont (Banks et al. 2017) is based on an ironstone (haematite) mine, while the rest are coal mines

several decades. Amongst the best known of these are the schemes at Springhill, Nova Scotia, Canada (Jessop 1995; Jessop et al. 1995; Michel 2009; Tweedie 2014), Park Hills, Missouri, USA (Watzlaf and Ackman 2006; DOE 2015), Marywood University, Pennsylvania, USA (Korb 2012), several in Saxony, Germany (Ramos et al. 2015) and megawatt-scale schemes at Barredo colliery, Mieres, northern Spain (Loredo et al. 2011, 2017; Ordóñez et al. 2012; Jardón et al. 2013) and at Heerlen, Netherlands (Minewater Project 2008; Ferket et al. 2011; Verhoeven et al. 2014). More recently, schemes have been documented in Eastern Europe, including those at Saturn colliery, Czeladz, Poland (Malolepszy et al. 2005; Tokarz and Mucha 2013) and Novoshakhtinsk colliery, Russia (Rostov Regional Government 2011; Ramos et al. 2015). A number of mine water heat pump schemes are also active in the United Kingdom (Fig. 1). Global reviews are provided by Banks et al. (2003, 2004), Watzlaf and Ackman (2006), Hall et al. (2011), Preene and Younger (2014), Ramos et al. (2015) and Bracke and Bussmann (2015).

Obstacles to the uptake of mine water heating and cooling

Banks (2016) listed several main obstacles to the uptake of mine water space heating and cooling, with an emphasis on the UK.

- Perceived risk of ochre clogging of pumps, heat exchangers, pipelines and reinjection wells.
- Risk of reinjected thermally spent (e.g. cool) water "breaking through" open mine pathways to the (e.g. warm) abstraction shaft or well.
- Uncertainty over legal and licencing issues—including the guaranteed longevity of mine pumping operations and abstraction licences, and the legal risk of accruing future liability for mine water pollution.
- Presence of a suitably dense long-term heating and cooling demand, with suitable heat emitters, in the vicinity of the mine. If this is associated with a new development, are conventional heating/cooling solutions already "locked in"?

To these can probably be added the difficulties of identifying suitable ownership, economic and distribution models: will an operator simply distribute mine water (or a fluid thermally coupled to the mine water) to individual consumers, each with their own heat pump? Or will an operator own a centralised heat pump plant room and a district heating and cooling network? In each case, where do ownership boundaries and responsibilities fall, and who owns the right to claim any state subsidies?

The EU Research Fund for Coal and Steel has funded a project entitled "Low Carbon Afterlife: Sustainable Use of Flooded Coal Mine Voids as a Thermal Energy Source—a Baseline Activity for Minimising Post-Closure Environmental Risks" (acronym: LoCAL; Gzyl et al. 2016), with several work packages, each specifically aimed at overcoming these barriers. The work reported in this paper specifically addresses the design and operation of heat exchange solutions to understand and minimise hydrogeochemical risks. Internationally, the Barredo shaft heat pump scheme at Mieres, northern Spain (Loredo et al. 2017), and the proposed Ewa shaft heat pump scheme at the Szombierki coal mine, Bytom, Poland (Janson et al. 2016), are included as LoCAL study sites, together with a number of schemes in the United Kingdom. The paper will examine, in turn, the British LoCAL study sites and summarise the experiences to date with each site.

Modes of operation for mine water heat pump/exchange schemes

There are a number of modes in which heat can be exchanged with mine water (Fig. 2, using terminology consistent with Banks et al. 2004; Banks 2012):

Open-loop systems with disposal of thermally spent water

Here, mine water is abstracted from a flooded mine via a shaft or boreholes and passed directly through a heat pump or (more commonly) a heat exchanger (coupled to a heat pump). After heat exchange, the mine water is rejected to surface water (or, sometimes, to the sea), often following some form of treatment (Fig. 2a). Examples of such schemes include the Barredo coal mine shaft at Mieres, Asturias, northern Spain (Loredo et al. 2011, 2017; Ordóñez et al. 2012; Jardón et al. 2013), where the water quality is relatively good and where no treatment is necessary, and the Caphouse colliery in Yorkshire, UK, (Burnside et al. 2016a), where heat exchange takes place prior to mine water treatment. Possible disadvantages of such open-loop schemes include: the cost of treatment and the potential for pumps, pipelines, heat exchangers and reinjection boreholes to become fouled with chemical precipitates (often iron oxyhydroxides—'ochre'—or manganese oxides).

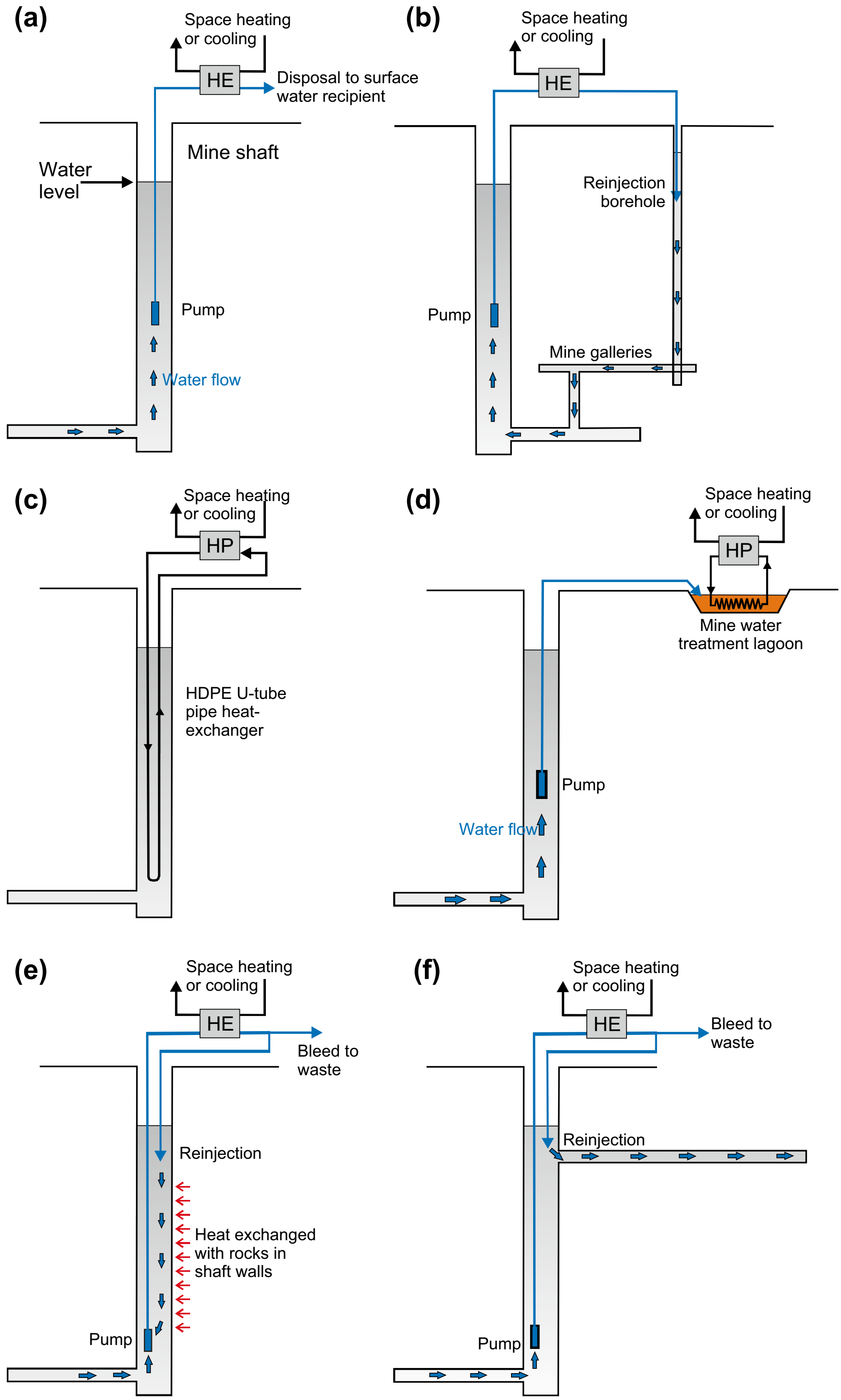
Open-loop systems with reinjection of thermally spent water

If treatment and disposal of mine water to surface waters is to be avoided, it is possible to reinject the water back into the mine workings, or to another aquifer unit, following heat exchange (Fig. 2b). The advantage of this is that water resources are conserved while treatment and disposal costs are avoided. On the other hand, it requires the drilling and maintenance of reinjection boreholes and runs the risk of thermal "feedback" if the connection between the abstraction and injection points is too direct. Examples of this type of scheme include Shettleston, Glasgow and Lumphinnans, Fife, Scotland (Banks et al. 2009) and Heerlen (Minewater Project 2008; Ferket et al. 2011; Verhoeven et al. 2014). In the latter scheme, the reinjected cool water (from heating) or warm water (from cooling operations) could theoretically be stored in the mine workings, allowing for later abstraction during the appropriate season.

Closed-loop systems

Here, a heat exchanger (which may be a steel radiator, or a loop of polythene pipe) is submerged in the mine water. This may take place in the mine itself (in a flooded shaft or gallery, Fig. 2c), as at Folldal mine in Norway (Banks et al. 2004; Ramos et al. 2015), or within a mine water treatment lagoon, after the mine water has been pumped to the surface, as at Caphouse, Yorkshire, UK (Fig. 2d, Burnside et al. 2016a). A heat transfer fluid is circulated through the heat exchanger, typically back to a heat pump servicing

Fig. 2 Different modes of heat extraction from/rejection to abandoned, flooded mines. **a** Open loop with disposal of water to surface recipient, **b** open loop with reinjection, **c** closed loop in flooded shaft, **d** closed loop in surface mine water treatment pond, **e** standing column with bleed and recirculation in shaft, **f** standing column configuration, with large natural flow up shaft. *HE* heat exchanger or heat pump, *HP* heat pump. Reproduced with the permission of © David Banks



a space heating/cooling demand. The main advantage of this system is that no mine water is abstracted and all issues relating to water chemistry and treatment are thus avoided. The main disadvantage is that, because mine water is not necessarily being deliberately mobilised by pumping, replenishment of heat to the heat exchanger takes place by conduction, natural advection and thermal convection of water in the mine void. The heat yield of closed-loop systems is thus often more limited than with open-loop systems.

"Standing column" systems

Here, water is abstracted from a specific depth in a mine shaft. It is passed through a heat exchanger and some or all of the water is returned to the same shaft at a different depth and different temperature (Fig. 2e). Any fraction that is not returned, but which is disposed of at surface, is known as the bleed fraction (if the bleed fraction is 100%, it is simply an open-loop system with disposal). The returned water usually flows along the shaft towards the pump, absorbing heat from (or, if warmer, rejecting heat to) the walls of the shaft. If there is no natural advection of water along the shaft, the heat gain is ultimately sourced from conduction through the surrounding rocks towards the walls of the shaft, and the sustainable heat yield will usually be rather limited (Fig. 2e). If there is natural water advection along the shaft, this will tend to thermally replenish the system, increasing the heat yield. If the natural advection along the shaft is very large, the reinjected water may flow away from the shaft before returning to the pump, effectively becoming decoupled from the pumping horizon (Fig. 2f).

British LoCAL study sites

In the United Kingdom, the LoCAL project monitors three coal mine study sites, representing each of the configurations listed above:

1. The Markham No. 3 shaft study site near Bolsover—a standing column system.
2. The Caphouse site, near Wakefield, which incorporates an open-loop mine water system with disposal to treatment lagoons, and
3. a closed-loop system installed in a mine water treatment pond.
4. The Shettleston site, a long-established, operational open-loop mine water system, with reinjection of thermally spent water.

At the Markham and Caphouse sites, monitoring systems have been implemented to evaluate the energetic performance of the heat pump schemes, by the installation of heat meters on the mine water and delivery sides of the heat pump, together with the monitoring of electrical power consumption. Furthermore, the hydrochemistry of the mine water is monitored on an approximate monthly basis, with the following parameters determined in the field: pH, dissolved O_2, Eh, total alkalinity, temperature, electrical conductivity and samples being collected for laboratory analysis of suites of major cations and anions, ^{2}H, ^{18}O and $^{34}SO_4^{=}$ stable isotopes and (more recently) dissolved methane. The detailed hydrochemistry of the two sites is fully documented by Burnside et al. (2016a, b).

In addition to these, a fourth study site, at the former Manvers Colliery, near Barnsley, South Yorkshire, is under development as a future open-loop system, with abstraction from, and reinjection to, two different levels of coal mine workings. This will not be discussed further in this paper as it is not yet fully operational (being at the permitting and licencing stage).

Caphouse, Yorkshire: open-loop system with discharge to surface water

Caphouse Colliery is located c. 9 km WSW of the town of Wakefield in West Yorkshire. It comprises several shafts including the Hope (1.6254°W 53.6418°N), Inman, Furnace and Caphouse (1.6182°W 53.6440°N) shafts and two drifts (Brown and Goodchild 1979; Kruse 2007). The colliery complex closed as a working mine in 1985, but has now been reopened as the National Coal Mining Museum of England (NCMME). Caphouse/Hope colliery is hydraulically interconnected underground to a wider network of collieries, including the workings of the Woolley (1.5338°W 53.5961°N) and Denby Grange Collieries (1.5942°W 53.6340°N) (INWATCO 2005a, b). The Hope Shaft is pumped every night and early morning (while electricity is cheap) to maintain mine water levels sufficiently low that (a) the museum's underground exhibits and visitor galleries do not flood and (b) to prevent uncontrolled outbreaks of ochreous mine water on a regional basis. The Hope Shaft is some 197 m deep and the submersible pumps are placed at c. 170 m depth (−23 m asl[1]), with mine water levels in the shaft being maintained in the range c. 143–156 m bgl[2] (+4 to −9 m asl). The average pumping rate is some 3000 m^3 day^{-1} (up to 76 L s^{-1} for 12–16 h day^{-1}). The mine water is treated in a passive aerobic aeration–settlement–wetland system, comprising an aeration cascade (with optional alkali dosing), two aeration basins, a balancing pond, four settlement basins (2×2 in parallel) and two parallel polishing reed beds, prior to discharge to the local stream (PIRAMID 2003, Banks 2007; Faraldo Sanchez 2007—Fig. 3).

[1] Above sea level.

[2] Below ground level.

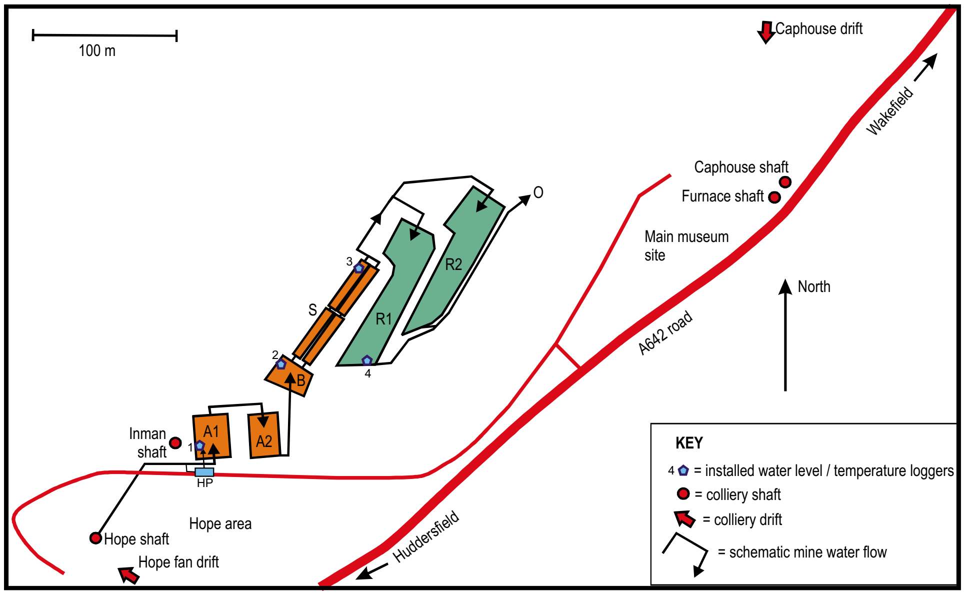


Fig. 3 Overview map of Caphouse Colliery site, showing (schematically) the pumped mine water flow through the aerobic treatment system. *HP* heat pump cabin, *A1* 1st aeration pond with aeration cascade at southern end, *A2* 2nd aeration pond, B balancing pond, *S* sedimentation basins, *R1* and *R2* reed beds, *O* outfall of treated mine water to stream. *1–4* installed water-level/temperature loggers

The water is pumped from the mine at typically slightly above 14 °C (although temperatures of down to 12 °C have historically been recorded). Presupposing the removal of 5 °C of heat via a heat exchange system, a flow rate of 3000 m^3 day^{-1} represents a potential heat yield of:

$$3,000,000 \text{ L day}^{-1} \times 5 \text{ K} \times 4.19 \text{ kJ L}^{-1}\text{K}^{-1} / 86400 \text{ s day}^{-1} = 730 \text{ kW} \quad (5)$$

Thus, a pilot space heating plant has been set up at Caphouse, based on a Vaillant Geotherm VWS 101/2 heat pump of nominal 10.5 kW heat output. This provides space heating (via a buffer tank and thence circulation of warm water through a conventional space heating radiator, with a flow temperature of 50–52 °C and a return of 45–46 °C) to a museum audiovisual exhibit in the building associated with the Inman shaft. A small portion of the pumped mine water is taken from the main pipeline between the Hope Shaft and the first aeration lagoon. This mine water offtake passes through a dual in-line mesh filter and then through two parallel (one operational, one standby) shell and tube heat exchangers before being discharged to the first aeration lagoon. Heat is transferred via the heat exchangers to a 20% solution of Hydratech Thermox FPG heat transfer fluid (based on propylene glycol), which is circulated through the heat pump evaporator (Fig. 4).

The water chemistry of the Hope Shaft mine water has been described in full detail by Burnside et al. (2016a) and will only be summarised here, with a representative analysis being presented in Table 1. The water is typically a sodium sulphate-(bicarbonate) water, which is likely to have formed by the mixture of an acid sulphate signature (derived from pyrite oxidation in the mined strata), with an ambient sodium bicarbonate water (which is typical of the deep British Coal Measures strata—Banks 1997; Banks et al. 1997b). During the past decade or so of pumping from Hope Shaft, the quality of the mine water has improved, with iron concentrations decreasing from c. 30 to c. 15 mg L^{-1}, and sulphate concentrations declining from c. 1200 to c. 600 mg L^{-1}. Since early 2015, the chloride concentrations increased to over 300 mg L^{-1} for reasons which are still not wholly clear. The Caphouse water consistently yields analyses of total iron somewhat higher than dissolved/ferrous iron (see Table 1), implying that oxidation of dissolved ferrous iron has commenced already in the workings or in the shaft. Indeed,

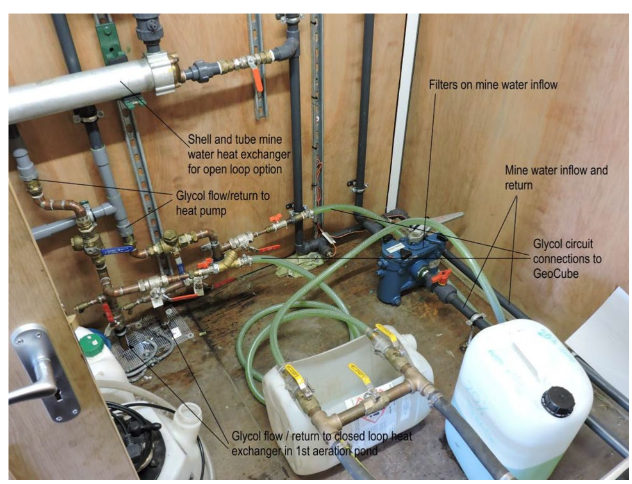


Fig. 4 Interface for open-loop (mine water circuit) and closed-loop options in Caphouse heat pump cabin. Optional couplings to GeoCube™ thermal response test rig also shown

Table 1 Characteristic water analyses from the LoCAL study sites' mine waters

	Shettleston	Caphouse	Markham regime 1	Markham regime 2
Field determinations	11/2/16	27/4/16		27/4/16
Temperature, °C	11.2	13.6	15.4[c]	13.3
pH	7.14	6.87		7.33
Dissolved oxygen, % saturation	21.8%[a]	18%		86%
Electrical conductivity, μS cm^{-1}	915	2733		2268
Redox potential, mV	+19[a]	−35		+79
Alkalinity, meq L^{-1}	6.80	7.59		5.04
Dissolved gases	11/2/16	27/4/16	15/10/12	27/4/16
CO_2, mg L^{-1}	nd	169[b]	nd	20.8[b]
CH_4, μg L^{-1}	nd	495[b]	9040	16.5[b]
Cations	11/2/16	26/9/14	15/10/12	17/9/15
Ca, mg L^{-1}	92	77	435	130
Mg, mg L^{-1}	37	47	218	43
Na, mg L^{-1}	36	417	3690	434
K, mg L^{-1}	5.3	9	110	26
Fe (dissolved), mg L^{-1}	0.79	14.1	19.2–19.7	0.13–0.16
Fe (total), mg L^{-1}	1.62	16.5	21.5	0.72
Mn, μg L^{-1}	214	660	3410	27
Ammoniacal-N, mg L^{-1}	nd	1	5.0	<0.01
Ba, μg L^{-1}	74	10	150	120
Sr, μg L^{-1}	475	710	5440	1040
Anions	11/2/16	26/9/14	15/10/12	17/9/15
Cl^-, mg L^{-1}	65.4	136	6590	829
$SO_4^=$, mg L^{-1}	58.1	640	1723	135
Alkalinity, meq L^{-1}	nd	9.57	8.69	6.25
NO_3^-, mg L^{-1}	0.54	nd	nd	3.1 (10/9/15)
F^-, mg L^{-1}	<0.5	nd	nd	nd
Br^-, mg L^{-1}	0.08	nd	nd	nd

Electrical conductivity is cited in μS cm^{-1}, where 1 S = 1 ohm^{-1} = 1 mho

nd not determined

[a]Dissolved oxygen and redox potential may be overestimated due to difficulties in avoiding contact with atmospheric oxygen during measurement

[b]Determined by analysis by British Geological Survey of samples collected in stainless steel gas-tight 'bombs'

[c]Typical value based on Athresh et al. (2015)

an underground inspection of the over-water-table workings reveals plenty of opportunities for partial oxidation of a portion of the mine water cascading into the dewatered upper workings.

One of the drawbacks of the open-loop scheme is that it can, of course, only be used when mine water is being pumped from Hope Shaft (i.e. night time and early morning, when electricity is cheapest). The filters prior to the heat exchangers require regular cleaning of ochre deposits by museum staff, reportedly up to several times each day (Fig. 5). Despite the filters becoming clogged, however, there have not been major issues with clogging of the shell and tube heat exchangers with ochre deposits, an observation which lends weight to the assertion by staff (HUNOSA pers. comm.; Loredo et al. 2017) of the Barredo/Mieres heat pump scheme in Asturias, Spain, that shell and tube heat exchangers are less susceptible to ochre clogging than parallel plate heat exchangers.

Athresh et al. (2016) reports on the performance of the Caphouse open-loop scheme, as measured by (1) a Kamstrup 602 Multical heat meter measuring the thermal energy supplied from the heat pump to a thermal buffer tank, (2) an identical heat meter measuring the amount of thermal energy extracted from the mine water and (3) an 'Autometer' A100MT electric meter measuring the electrical power consumed by the heat pump unit. He reports that the heat pump (not including the electricity consumption of the shaft submersible pump, as this must be operated in

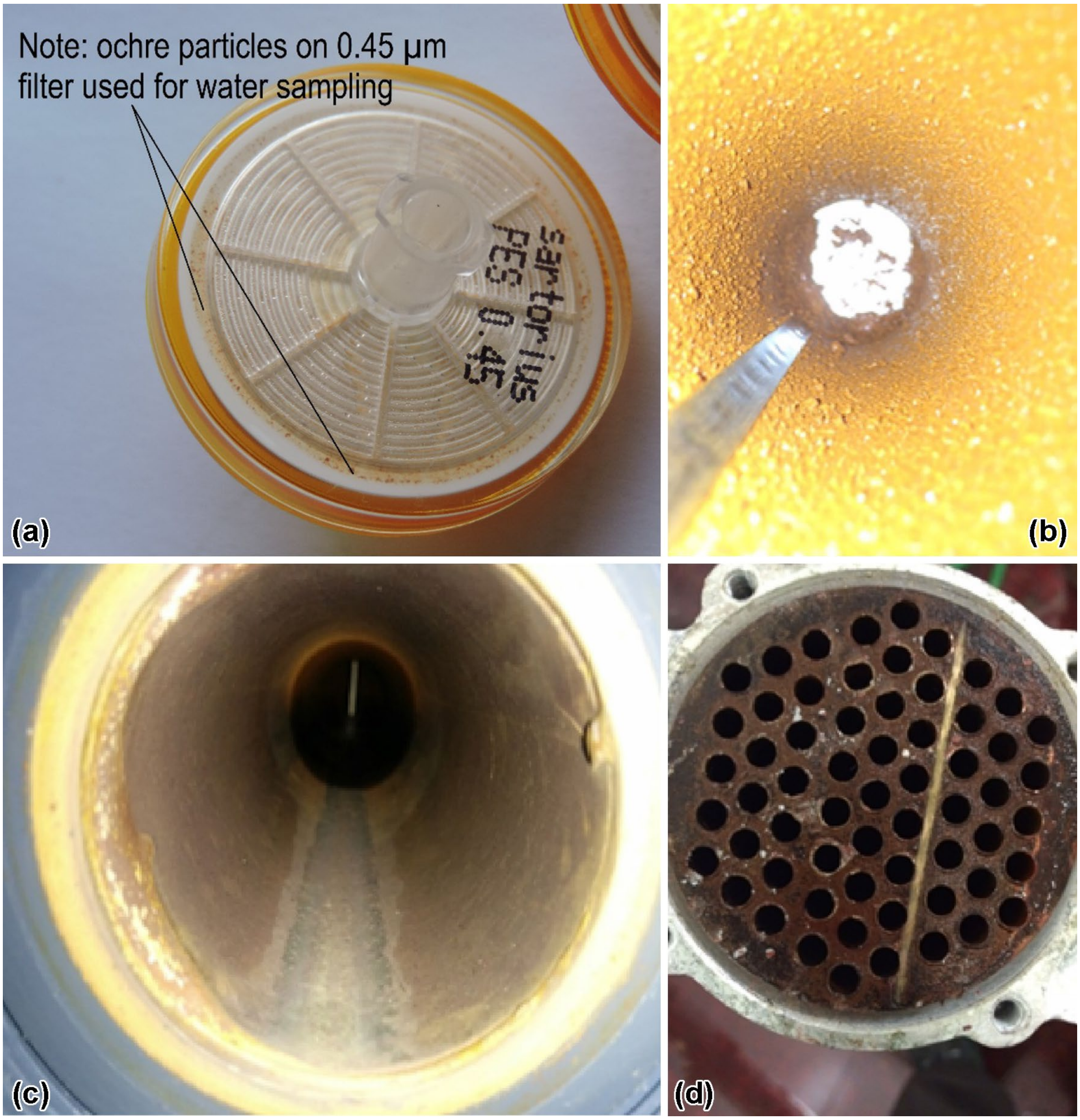


Fig. 5 **a** A 0.45 µm filter used for water sampling at Shettleston. Note the many small ochreous particles retained on the filter; **b** the interior of a mine water strainer from Caphouse (significant ochre accretion), after 4 days' operation; **c** the interior of a mine water pipe from Markham and **d** shell and tube heat exchanger (from Markham), both after 2.5 years' operation (no ochre accretion)

any case for dewatering purposes) exhibits a coefficient of performance (ratio of useful heat supplied to buffer tank to electricity consumed by heat pump) varying from 3.5 to 4.0, with a mine water inflow temperature of around 14.5 °C and a temperature differential across the mine water heat exchangers of 5–6 °C.

Shettleston, Glasgow: open-loop system with reinjection

Shettleston (4.1669°W 55.8501°N) is amongst the oldest of Britain's mine water heat pump schemes, having been commissioned in 1999 to provide space heating and pre-heating of domestic hot water to 16 social housing apartments in eastern Glasgow, Scotland. The early operation of the scheme was documented by Banks et al. (2009). In principle, the scheme abstracts mine water from a borehole (reported to be up to c. 100 m deep) with a submersible pump, passes the water directly through the evaporators of two heat pumps and then returns the thermally spent water to a shallower reinjection borehole situated some 37 m away. The abstraction borehole is believed to penetrate abandoned workings, probably of the Ell or possibly the slightly deeper Glasgow Main, Splint or Virgin seams (Burke 1998). It is not wholly clear whether the injection borehole returns water to a higher level of mine workings or simply to permeable horizons in the Carboniferous (Westphalian) Coal Measures aquifer sequence. The heat pumps currently employed are two Danfoss BW10-025 units each of nominal 31–34 kW heating capacity (for a nominal water inlet temperature of 10 °C).

To date, the system has run with relatively few operational problems and few issues with clogging of the evaporator heat exchangers themselves have been experienced. The water chemistry is normally similar to a rather conventional calcium bicarbonate groundwater and is rather low in dissolved iron. The fact that total iron is around double the dissolved iron in the analysis of Table 1, together with the observation of small ochre particles on sample filters, suggests that the iron in the water is already partially oxidised underground to form small ochre flocs (Fig. 5). It is reported that the mine water can episodically become very ochreous, as if iron oxyhydroxide particles are being flushed out of the mine system. It is suspected, but not yet established, that these episodes may be related to high rainfall episodes. The ochreous episodes can lead to in-line filters becoming clogged on the water supply line to the heat pump, resulting in head loss and the necessity for regular clearance. Furthermore, the reinjection borehole has reduced in capacity with time and currently a proportion of the spent water is run to waste at surface rather than being reinjected. The Shettleston site has only recently been incorporated into the LoCAL project and hence available data are very limited and the site will not be discussed further in detail.

Markham No. 3, Derbyshire: "standing column" system

Markham Colliery, located just north of Bolsover, Derbyshire, UK, comprises four main shafts. The site (1.3285°W 53.2424°N) of the two southern shafts (shafts nos. 2 and 3) is now occupied by a short-term operating reserve (STOR) gas engine electricity generation station, operated by the firm Alkane Ltd., and supplying peak load electricity to the National Grid to augment the electricity supply whenever a high demand or a reduction in conventional electricity supply is anticipated. Since 1904, Markham colliery worked coal from a number of seams of the Westphalian Lower and Middle Coal Measures strata (Sheppard 2005).

Markham No. 3 shaft is the only one of the shafts that has not been backfilled, following abandonment in around 1993. The shaft was brick-lined at 15 ft (4.6 m) diameter and was reportedly c. 490 m deep (healeyhero 2015), although shafts 1 and 4, with which shaft 3 interconnected, reached the Blackshale coal at c. 630 m deep (Burnside et al. 2016b). As at Caphouse (above), Markham colliery is a part of a wider network of hydraulically interlinked abandoned collieries, including those at Arkwright (53.2296°N 1.3633°W), Bolsover (53.2350°N 1.3116°W), Duckmanton (53.2447°N 1.3521°W) and Ireland, Staveley (53.2626°N 1.3456°W). Markham No 3 Shaft was left largely open, following abandonment, with a hydraulically open plug at the level of the Ell seam (−357 m asl), to allow venting of mine gas. This gas was initially used to power the gas engines at the Alkane site. However, as mine water levels rose following the post-abandonment cessation of pumping, the methane yield declined as methane-rich horizons became submerged. Deliberate methane abstraction ceased in 2006, and now imported gas is used to fuel the gas engine generators, although water levels in the shaft continue to rise. To give some impression of the rate of rise, in May 2011, the water level was 239.5 m bgl (−167.7 m asl), while by February 2016 it was at 136 m bgl (Fig. 6).

In 2012, Alkane started trialling a pilot heat pump project based on mine water from No. 3 shaft. A 'standing column' type arrangement was installed, with an electric submersible pump (6″ Franklin VS14/20 with motor rated at 11 kW) installed at a short distance below the (then) water level at 235 m bgl (Athresh et al. 2015). As at Caphouse, the pumped water (at c. 14–15 °C) was passed through a mesh filter and then a sealed shell and tube heat exchanger arrangement, thermally coupled via a secondary circuit of heat transfer fluid to a Danfoss DHP-R 20 kW heat pump (Fig. 7). The thermally spent mine water at around 12–13 °C was returned, without atmospheric contact, via a reinjection main down the shaft to be released to the water column via a diffuser at 250 m bgl (this arrangement is referred to as standing column Regime 1—Fig. 6). No net abstraction of mine water thus takes place at Markham (Athresh et al. 2015). The heat pump supplies hot water at 52–55 °C to a buffer tank, which thereafter supplies hot water for space heating (via a combination of radiators, fan coil units and underfloor heating) to the Alkane on-site office complex. Return water to the heat pump is typically at c. 45–46 °C.

The overall efficiency of the system is compromised by the amount of electricity required to pump some 2 L s^{-1} of mine water up in excess of 200 m. Around April 2014, Athresh et al. (2015) estimated the system COP (heat supplied divided by electricity consumption by heat pump and submersible pump, based on idealised heat pump characteristics and estimated minimum energy required for pumping) to be no greater than 2.7. Athresh et al. (2015) also predicted that a system COP of 3.95 could be achieved if the mine water level rose to within 15 m of the surface.

In January 2015, mine water levels had risen, allowing the entire standing column arrangement to be raised in the shaft (thus potentially saving on pumping costs). The pump was re-positioned at 170 m bgl, with the reinjection diffuser

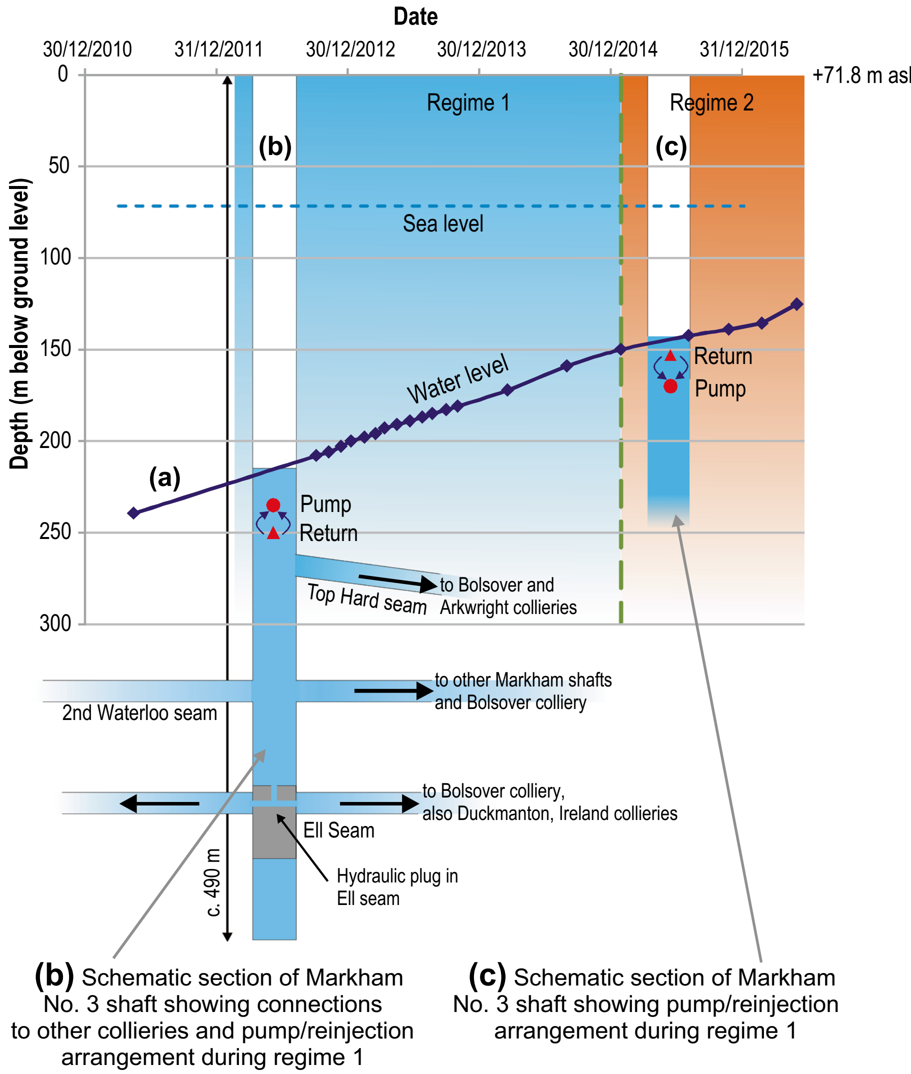


Fig. 6 **a** Graph showing rate of increase in mine water level in Markham No. 3 shaft, with **b** a superimposed section of the shaft, showing interconnections to other collieries and the arrangement of pump and reinjection return during pumping regime 1, and **c** abbreviated section of the shaft, showing arrangement of pump and reinjection return during pumping regime 2. Modified from Burnside et al. (2016b)

now being set 17 m above the pump at 153 m bgl (known as standing column Regime 2—Fig. 6). Following this, the pumped water temperature appears to have fallen somewhat to 13–14 °C. As at Caphouse, the mine water has been regularly sampled (Burnside et al. 2016b, Table 1) and the performance of the system monitored, since January 2015, using (1) a Kampstrup 602 Multical heat meter measuring the thermal energy supplied from the heat pump to the thermal buffer tank, (2) an identical heat meter measuring the amount of thermal energy extracted from the mine water and (3) two electric meters, one measuring the electrical power consumed by the heat pump unit and the other measuring the power supplied to the submersible pump. An actual system COP (heat output divided by electrical consumption by the heat pump and submersible pump) of 1.9 has recently been calculated. Despite the submersible pump being fitted with a frequency controller and being run at 43 Hz and 5.2 kW power, it is clear that the electricity consumption by the submersible pump is detrimental to the overall efficiency.

The gas engine generators at the site have to be pressed into service within a couple of minutes of the National Grid requesting additional power. Thus, the engines have to be pre-warmed to enable a start at short notice. Previously an electric heater was used to pre-warm the engines but, most recently, the system has been modified so that the heat pump also pre-warms the gas engines. Moreover, when the engines are running, the facility also exists for the gas engines to feed exhaust heat back into the buffer tank on the space heating circuit on the condenser side of the heat pump, negating the need for heat pump operation during such episodes and enhancing the overall COP of the system (although the gas engines are only typically operated every few days to provide peak load electricity).

It was initially assumed that the Markham No. 3 mine water would be rather saline and highly reducing (as the water degasses natural dissolved methane which

Fig. 7 Markham No. 3 Shaft heat pump system. **a** Two of the authors (AA and NB) at the shaft top; **b** mine water filter (relatively unclogged); **c** shell and tube heat exchangers, marked as HE (pump shown is used for filling and pressurising glycol circuit)

occasionally needs to be dispersed by air blowers in the shaft). During initial trial pumping of the shaft from 250–340 m depth, electrical conductivities in excess of 40,000 µS cm^{-1}, and ammoniacal nitrogen concentrations of 14 mg L^{-1} were recorded, with very low sulphate concentrations indicative of sulphate-reducing conditions (Burnside et al. 2016b).

Following the installation of the standing column Regime 1, the water quality was still relatively saline, with electrical conductivities of 20,000–25,000 µS cm^{-1}, dominated by sodium and chloride, but with 500–1700 mg L^{-1} sulphate. Concentrations of 4–5 mg L^{-1} ammoniacal nitrogen, 3–4 mg L^{-1} Mn and up to 9 mg L^{-1} methane all suggested broadly reducing conditions (although not necessarily sulphate reducing). Iron concentrations were typically 20–22 mg L^{-1}, though occasionally falling to slightly below 4 mg L^{-1}, and the iron appeared to be in its dissolved ferrous form. No problems were noted with clogging of the filters or heat exchangers with ochre deposits or other scale. This is presumed to be because iron remained reduced and soluble and was not exposed to atmospheric oxygen.

Following the raising of the standing column arrangement (regime 2), the mine water quality changed substantially, suggesting that there is likely to be stratification of the water column within the mine shaft, with fresher, less reducing water occupying the uppermost portion. The electrical conductivity declined to 2000–3000 µS cm^{-1} (although still Na–Cl dominated), sulphate to a few 100 mg L^{-1}, ammonium and methane dropped to very low levels and nitrate was detected at 3–5 mg L^{-1}. Manganese fell to <100 µg L^{-1} and iron to 310–720 µg L^{-1}. Significantly, the dissolved iron was less than the total iron, suggesting that, now, some iron oxidation and hydrolysis might be taking place in the shaft itself. This has not yet manifested itself as problems with ochre clogging of filters or heat exchangers, however, possibly due to the low total iron concentrations available.

To date, no problems of long-term decline of temperature, relating to thermal feedback of reinjected cool water to the abstraction pump, have been noted (possibly reflecting the low pumping rate relative to the volume and cross section of the shaft, or maybe reflecting some water movement within the shaft), nor has any tendency towards ochre (or other) clogging of filters or heat exchangers (Fig. 5).

Caphouse, Yorkshire: closed-loop system

As an alternative to the open-loop scheme described above, at Caphouse Colliery the Vaillant Geotherm VWS 101/2 10.5 kW heat pump has the additional possibility of sourcing its energy from a closed-loop heat exchanger submerged in aeration pond A1 (Fig. 3). Because pond A1 always contains mine water, even when Hope Shaft is not being pumped, the closed-loop system can be used at any time of the day. The water temperatures and levels are continuously logged in the 1st aeration pond (A1, logger 1 in Fig. 3), the balancing pond (B, logger 2), near the outlet of the sedimentation basins (S, logger 3) and near the outlet of the upper reed bed (R1, logger 4). A typical time series for one week in summer (August 2015) is shown in Fig. 8.

The water levels in the aeration pond clearly show the times of pumping (night and early morning) of Hope Shaft. During the daytime, there is little flow in the aeration pond and the water heats up, reaching a maximum of over 16 °C in early evening. Thereafter the water cools but drops, immediately when the Hope Shaft pumps are switched on, to a temperature a little above 14 °C (the mine water temperature). In the deeper balancing pond (B), temperatures reach around 15 °C during the day but as the Hope Shaft starts pumping, the warm water overflows from the aeration ponds into the balancing pond, causing a short-lived peak in temperature, which then drops off towards the mine water temperature. The temperature variation is even more subdued in the sedimentation pond. At the exit from the reed bed, however, the shallow slow water flow has been vulnerable to atmospheric temperature fluctuations and daytime temperatures of over 17 °C are reached.

During the winter (Fig. 8), almost the opposite picture emerges. As the Hope Shaft starts pumping in the evening, the water temperature in the 1st aeration pond increases to a constant 14 °C (the mine water temperature). After pumping ceases, the temperature drops slowly, depending on the air temperature. During the winter of 2015–16, however, the aeration pond seldom dropped below 11.5 °C. The balancing pond shows a similar pattern, but generally 0.5–1 °C cooler during pumping and several °C cooler when the Hope Shaft was not pumping. The sedimentation pond temperatures generally correspond to the balancing pond (B) but in a much more subdued form. As in summer, the reed bed outlet temperatures are much more susceptible to atmospheric interaction (heat losses during winter, especially at night).

The closed-loop heat exchanger is an NRS "Energy Blade 3K4" comprising four parallel 3 m × 0.49 m heat exchange panels in 304 stainless steel (Fig. 9), giving a total heat exchange surface area of 11.8 m^2, mounted on a frame and submerged in the 1st aeration lagoon (A1 in Fig. 3). The nominal heat exchange capacity is cited as 8 kW in standing water (Nuenta 2015), which makes it suitable for coupling to a 10.5 kW heat pump, which, at a COP of 4 would be extracting 10.5 kW × 0.75 = 7.9 kW from the lagoon. The Energy Blade is coupled into the heat pump's heat transfer fluid circuit via insulated flow and return pipes. The entire system is filled with 20% propylene glycol-based Hydratech Thermox FPG heat transfer fluid. The relatively low percentage of anti-freeze was selected in order to reduce fluid viscosity in a relatively long hydraulic circuit, in the knowledge that the aeration lagoons maintain a temperature well above 10 °C all year. The heat transfer fluid is circulated by the heat pump's source-side circulation pump. The system has worked very satisfactorily since installation and is preferred over the open-loop system (above) by the Caphouse museum staff for two reasons (1) it can be used at any time and is not dependent on the Hope Shaft pumping at the time of operation, (2) no mine water is passed through the heat exchange/heat pump system, removing issues with ochre clogging or clearing of filters. During operation, the glycol circuit typically runs with a temperature differential of 5 °C, with fluid entering from the Energy Blade at 10.4 °C and leaving the evaporator at 5.3 °C. The relatively high differential suggests, in turn, that the heat pump's circulation pump is somewhat undersized for the optimum flow rate.

Two thermal response tests have been carried out on the Energy Blade using a GeoCube™ test rig manufactured by Precision Geothermal (2016). This rig

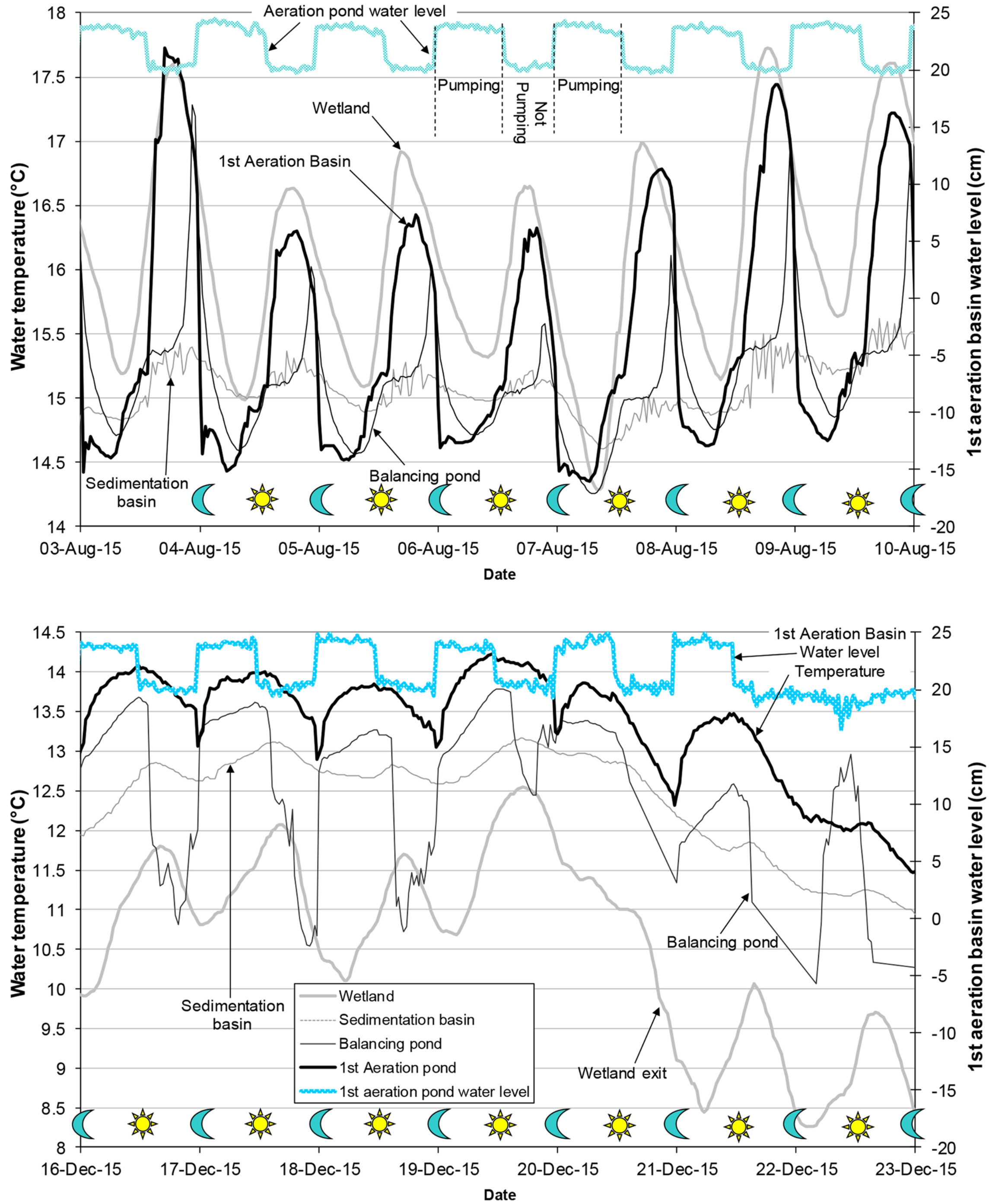


Fig. 8 A typical (*top*) summer (August 2015) and (*bottom*) winter (December 2015) week of water temperature fluctuations logged in loggers 1 (1st aeration pond, A1 in Fig. 3), 2 (balancing pond, B), 3 (sedimentation pond, S) and 4 (outlet from reed bed wetland R1) in Caphouse mine water treatment system. The water level (cm head over logger sensor) shows periods of pumping of Hope Shaft. The crescent moons indicate night time (tick on *x*-axis at midnight) and suns indicate daytime

essentially consists of a circulation pump, an array of electrical resistance heater elements capable of delivering up to c. 7.5 kW constant heat input, a flow meter and flow and return temperature sensors. The test rig is coupled to the Energy Blade via the heat transfer fluid circuit (Fig. 4) and a constant heating load is applied. The rate of heat loss through the Energy Blade can thus be measured and its heat transfer coefficient determined. The first test was run on 8th–9th October 2015 (Fig. 10) and was run for just over 21 h. Heat transfer coefficients

Fig. 9 The Energy Blade™ (**b**) prior to and (**a**) during installation in Caphouse No. 1 aeration lagoon; (**c**) aeration lagoon No. 1 prior to desludging (2013) and (**d**) aeration lagoon No. 2 following desludging (2013). Photographs reproduced with kind permission of Mr Alan Chalkley, National Coal Mining Museum of England

of around 900–1000 W K^{-1} (76–85 W m^{-2} K^{-1}, given a cited heat exchange surface of 11.8 m^2) were measured when the Hope Shaft was not pumping and the water in the aeration lagoon was immobile. When the Hope Shaft was pumping water through the aeration lagoon, however, the heat transfer coefficient increased to 1140–1180 W K^{-1} (97–100 W m^{-2} K^{-1}). This is significantly less than the heat transfer coefficient of 200 W m^{-2} K^{-1} claimed by Nuenta (2015) and is likely to be due to the GeoCube not achieving the minimum flow rate of 0.9 L s^{-1} recommended by the manufacturer (the rather small circulation pump of the GeoCube was only able to maintain a flow rate of some 0.4 L s^{-1}, which would likely have resulted in turbulent flow not being achieved within the heat exchanger and thus the heat exchange capacity being reduced). Another possibility was that the Energy Blade had become partially submerged in the ochre sediment which accumulates at the base of the aeration lagoon and this had interfered with the heat exchange capacity. In fact, the aeration lagoon was emptied and desludged during 20th–27th October 2015. The test was re-run on 27th–28th April 2016 (Fig. 11), to evaluate whether desludging has improved the heat transfer performance of the blade. In fact, the

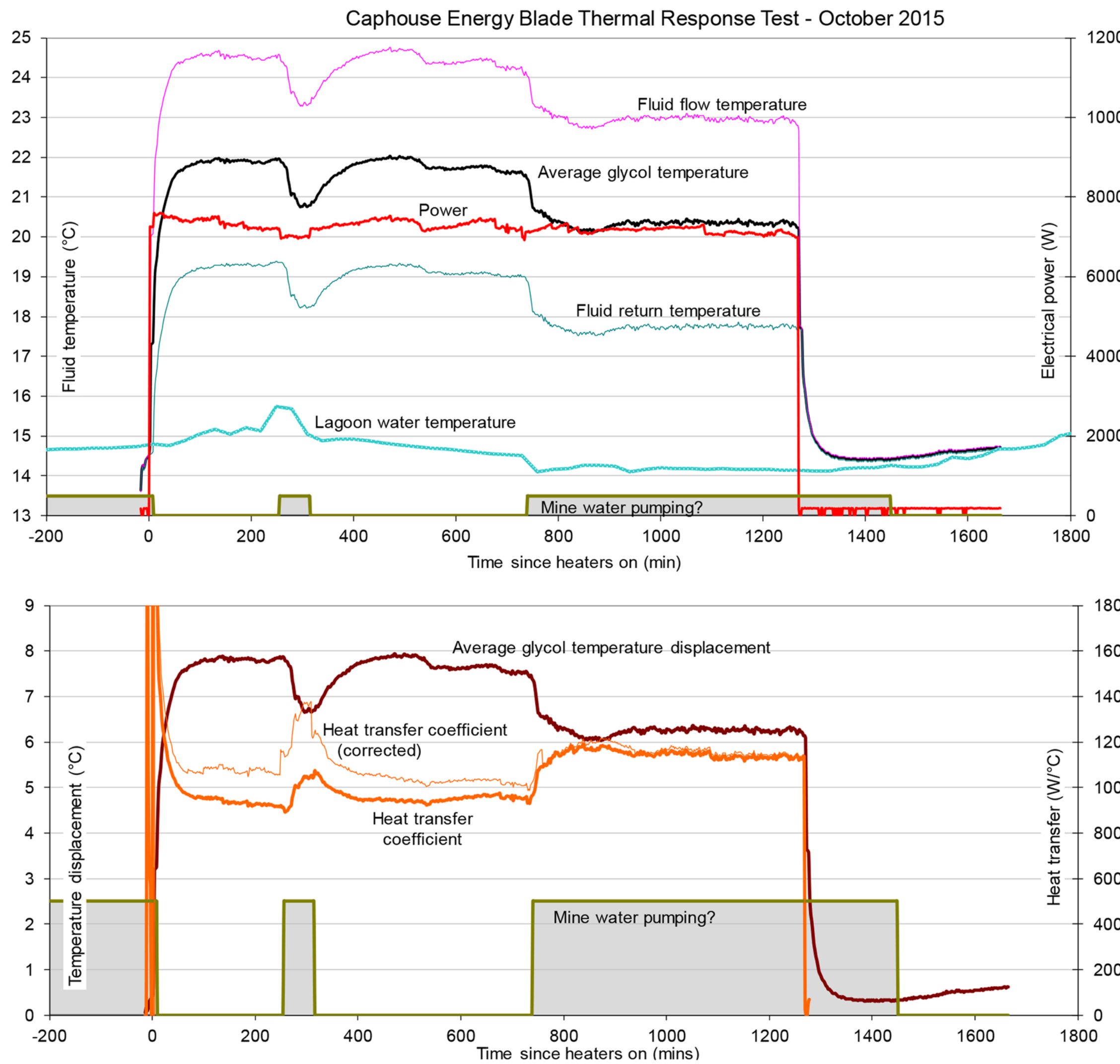


Fig. 10 Thermal response test on aeration lagoon heat exchanger, October 2015. The *upper diagram* shows the calculated electrical heater power (*W*), the glycol flow and return temperatures, the average glycol temperature, the lagoon water temperature from logger 1 and whether the mine water was pumping (shaded on/off). The lower diagram shows the glycol temperature displacement, relative to a baseline of 14.1 °C, the calculated heat transfer coefficient, relative to a lagoon baseline of 14.1 °C, a "corrected" heat transfer coefficient relative to the actual logged lagoon temperature, and whether the mine water was pumping (on/off)

heat transfer capacity appears to have decreased slightly in April 2016, although the exact values calculated depend on the assumptions about the baseline temperature of the mine water lagoon, which varies throughout the test. Given this uncertainty, there is no significant difference between the results of the two tests.

Discussion and conclusions

It is possibly best to sum up the findings of this paper as advantages and disadvantages associated with each of the options discussed:

Open-loop systems

Advantage: scalable

Open-loop schemes can be up-scaled simply by adding additional heat exchange capacity (and treatment capacity/reinjection boreholes, if necessary). The ultimate limit on the heat that can be extracted is simply (a) the quantity of mine water that is pumped or discharged and (b) the temperature differential that can be achieved across a heat exchanger. It is not coincidental that the largest mine water heat pump schemes in the UK (Egremont, Cumbria—only a pilot scheme, of 103 kW, Banks

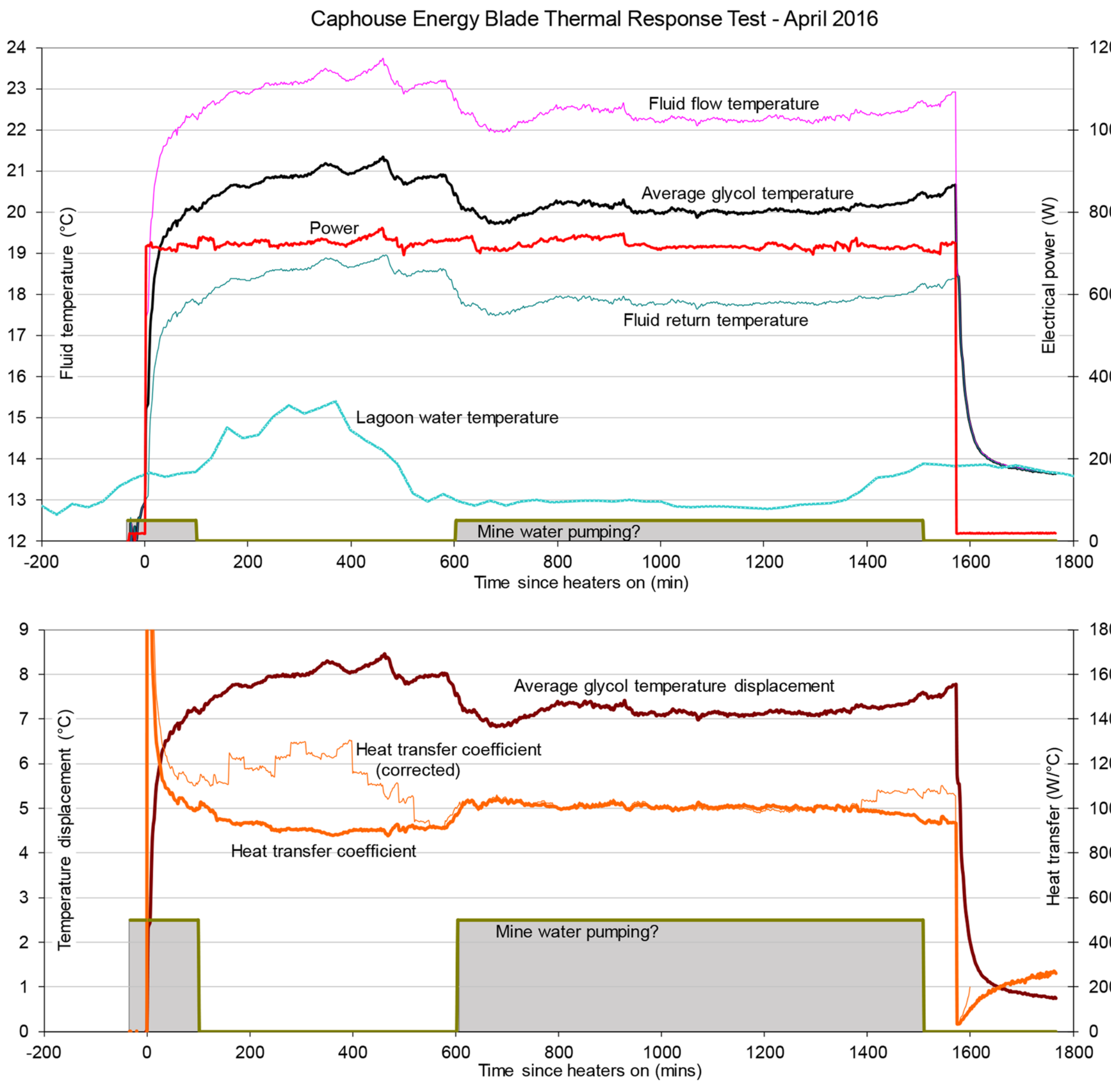


Fig. 11 Thermal response test on aeration lagoon heat exchanger, April 2016. The *upper diagram* shows the calculated electrical heater power (*W*), the glycol flow and return temperatures, the average glycol temperature, the lagoon water temperature from logger 1 and whether the mine water was pumping (shaded on/off). The lower diagram shows the glycol temperature displacement, relative to a baseline of 12.9 °C, the calculated heat transfer coefficient, relative to a lagoon baseline of 12.9 °C, "corrected" heat transfer coefficient relative to the actual logged lagoon temperature, and whether the mine water was pumping (on/off). In this test, the lagoon warmed significantly naturally during the day (when the mine water was not being pumped): this led to an apparent increase in heat transfer coefficient due to the decreased temperature differential between the heat exchange fluid and the lagoon water. The "corrected" heat transfer coefficient may, however, be an overestimate, if the logger (which is installed close to the lagoon sides and at shallow depth) is not representative of the deeper, probably cooler, water surrounding the heat exchanger. The "uncorrected" heat transfer coefficient may thus be more reliable

et al. *in press*) and in the world (MW-scale schemes at Mieres, Spain and Heerlen, Netherlands) are all open-loop schemes.

Disadvantage: risk of chemical (ochre) precipitates

The Coal Authority's Dawdon mine water heat pump scheme (Watson 2012; Bailey et al. 2013) found that passing iron-rich aerated mine water through a heat exchanger led to very rapid ochre clogging. In the case of Dawdon, this was solved using raw, unaerated mine water. This supports the observations and modelling work of Banks et al. (2009), which indicated that chemically reducing, iron-rich mine water can be used in heat exchange systems provided that it is not allowed to come into contact with atmospheric oxygen (or other oxidising agents), such that the iron remains in its soluble ferrous (Fe^{2+}) form (this conclusion is also supported by research into ochre clogging of land drainage systems—Abeliovich 1985). The observations from the LoCAL study sites also support this hypothesis—for example, the fact that the Markham No. 3 system operated under Regime 1 with no serious clogging issues, despite the relatively high reduced iron concentrations.

However, the LoCAL project seems to have demonstrated that not all mine waters are sufficiently chemically reducing to rely on iron always being present in its ferrous form. Indeed, there appears to be a subset of coal mine waters where oxidation of iron has commenced in the underground workings or shafts, such that ochre particles can be observed in the raw water, or where ochre clogging occurs, even where access to the atmosphere is precluded in the surface headworks (Caphouse, Shettleston). This can be diagnosed by analysing the ratio of total to ferrous iron in water analyses or by examining on-site filters (e.g. used for water sampling) for ochre particles. The presence of modest quantities of ochre particles (e.g. Shettleston) does not necessarily render a heat exchange scheme unworkable, and can be managed by a degree of maintenance. Where reinjection is practised, however, the presence of even small amounts of particulate matter can lead to a decline in the reinjection efficiency with time.

As regards mineralogical composition, ochre collected from the Caphouse mine water treatment basins was analysed by X-Ray Diffraction; although calcite was detected as a component, no prominent iron mineral peaks were noted, leading to the inference that the ochre largely comprises amorphous ferric hydroxide. Iron deposits from plate heat exchangers of the Spanish Barredo site were also found to be mainly amorphous ferric hydroxide, with a 6.3% $CaCO_3$ content, minor Mn-oxide content, and also with a detectable goethite (α-FeOOH) component (Loredo et al. 2017). Ochre deposits from the interior of the mine water pipe at the Scottish Shettleston scheme were also found to contain goethite.

In the future, the LoCAL project plans to experiment with dosing the mine waters with sodium bisulphite ($NaHSO_3$) or sodium dithionite ($Na_2S_2O_4$) prior to heat exchange, in an attempt to maintain iron in reduced form in solution (Dudeney et al. 2003). These reducing agents can be regarded as relatively environmentally benign, oxidising to form a solution of sodium and sulphate.

Disadvantage: difficulties in disposing of thermally spent water

While, in theory, the reinjection of iron-rich mine water is feasible, via a thorough understanding of chemistry (as at Heerlen, Netherlands), some difficulties in reinjection have been experienced at two Scottish schemes (Banks et al. 2009), due to the oxidation of dissolved iron and/or the presence of ochre particulates in the raw water. Thus, large open-loop mine water heat pump schemes will often be best suited to waters which (a) are already pumped for regional mine water management purposes and which are already treated prior to discharge to the environment (i.e. no additional pumping or treatment costs—e.g. Caphouse), or (b) which have low enough iron concentrations (and have good enough quality otherwise) that they can be disposed of directly to a surface watercourse (e.g. Egremont, Cumbria and Mieres, Spain), or, failing that, (c) are of reducing chemical quality and where pre-oxidised ochre and other particles are absent, such that reinjection can be practised.

Closed-loop systems

Advantage: does not depend on mine water pumping

Although the LoCAL project's experiences at Caphouse indicate that a flow of mine water over a submerged heat exchanger does increase its heat transfer capacity, submerged closed-loop heat exchangers (in mines or in treatment basins) do not require a constant flow of mine water to function. They can thus be operated independently of any mine water pumping regime.

Advantage: managed fluid quality

No mine water is pumped, reinjected or circulated through heat exchangers/pumps in a closed-loop scheme. The fluid circulated is a heat transfer fluid of controlled composition (usually based on a solution of glycol). This obviates any issues with heat exchanger clogging or serious corrosion. On the other hand, it has been noted at Caphouse that the submerged heat exchanger becomes progressively fouled by accumulating ochre deposits in the aeration basin. We have, however, not been able to demonstrate that this, in itself, adversely affects heat capacity (the underperformance noted was likely due to inadequate heat transfer fluid flow rates).

Disadvantage: slightly less efficient

It can be seen, at Caphouse, that while the open-loop mine water scheme is based on mine water at 14 °C, the closed-loop scheme requires a temperature differential to absorb heat from the lagoon to the heat transfer fluid. Thus, the fluid returns from the lagoon to the evaporator typically at around 10.4 °C. This (together with the parasitic power required to circulate the heat transfer fluid) would be expected to result is a modestly lower heat pump efficiency.

Disadvantage: less readily scalable

Although, in theory, one could multiply the number of submerged heat exchangers in the aeration pond to increase the heat extraction, the amount of installed hardware could soon become unmanageable. For example, the Energy Blade extracts some 8 kW nominal heat capacity. To abstract the total potential of some 730 kW (Eq. 5) would require some 91 units. While a single unit can easily be lifted or moved when the aeration basin requires desludging of accumulated ochre, tens of units would undoubtedly prove off-putting to museum maintenance staff (it should, however, be noted that successful MW-scale closed-loop heat exchanger projects have been installed in very large natural lakes and reservoirs, which have no need for desludging or periodic removal, such as at Kings Mill Hospital, Mansfield, UK—Banks 2012).

Standing column systems

Advantage: may avoid licencing issues, need for treatment

Experiences at Markham No. 3 would suggest that standing column systems can work very successfully if the heat loads are modest. At Markham, very little additional infrastructure was required (submersible pump, controls, rising main, recharge main, heap exchangers, heat pump), given that the deep, large diameter open shaft already exists. No reinjection boreholes, no water treatment (other than venting of methane) and no surface disposal facilities were required. Under some legislative regimes, it may be possible to argue that, as no net abstraction is taking place and as water is being returned to the ground at the same quality as that abstracted, then no abstraction licences or discharge consents are necessary. This will, however, depend on the legal framework in each individual country.

Disadvantage: may not be scaleable

The modest 20 kW scheme at Markham appears to work very well, if one disregards the rather large parasitic submersible pump power caused by the deep water level. The larger (103 kW) pilot scheme at Egremont (Banks et al. 2017) also successfully operated for a short trial period. However, monitoring of temperatures during the Egremont trial suggested that the heat extractable by a pure standing column arrangement might be limited to no more than 100 W m^{-1} (or several tens of kW for a typical deep mine shaft of several 100 m depth). If natural advection is occurring within the shaft, however, replenishing the thermal resources, significantly greater heat yields might be available.

Table 2 Summary of advantages and disadvantages of the various mine water heat exchange configurations shown in Fig. 2

Configuration	Open loop with discharge	Open loop with reinjection	Closed loop	Standing column
Examples	Caphouse, Mieres (Spain), Dawdon	Shettleston, Heerlen (Netherlands)	Caphouse	Markham, Egremont
Risk of ochre clogging	High, if water iron-rich and especially if exposed to oxygen	High, if water iron-rich and especially if exposed to oxygen	No	High, if water iron-rich and especially if exposed to oxygen
Legislative burden (licences, permits)	High	High	Low	Modest (depending on regulatory regime)
Energy efficiency of heat pump	High	High	Lower	High or lower, depending on degree of thermal feedback
Parasitic power loss (submersible pump)	Can be high (depending on mine water depth)	Can be high (depending on mine water depth)	Low (circulation pumps only)	Can be high (depending on mine water depth)
Potential thermal capacity	Large	Large	Modest	Modest, unless abstraction and reinjection hydraulically decoupled
Other advantages	Can be attractive if mine water is already pumped and treated for water management purposes	No treatment required	Controlled fluid quality. Can be installed in surface lagoons and ponds	Single site. No water transfer or treatment required
Other disadvantages	Cost of water treatment. Potential impact of temperature change on water treatment	Potential risk of clogging of reinjection boreholes. Requires at least two boreholes or shafts and water transfer pipe between them		

Concluding statement

The LoCAL project has successfully demonstrated the use of the four main mine water heat exchange configurations (open loop with discharge to surface water, open loop with reinjection, closed loop and standing column). Of these, the modest closed-loop scheme at Caphouse and standing column scheme at Markham have proved least problematic to operate (fewest problems with ochre clogging). The relative advantages and disadvantages of the schemes are summarised in Table 2. Although energy efficiency data are still being collected, the open-loop schemes may prove to be the more efficient schemes and are also likely to prove the most up-scalable. Among the outstanding issues that need to be investigated are:

1. can mine waters be successfully chemically dosed with environmentally benign reducing agents to hinder the oxidation and precipitation of ferric iron and manganese?
2. will altering the temperature of mine water (by heat extraction or rejection) adversely or favourably affect the efficiency of mine water treatment processes such as those at Caphouse (e.g. solubility of O_2, CO_2, rates of oxidation, hydrolysis, ochre nucleation and aggregation, rates of settlement, rate of growth of reeds in reed beds—Raftery 2016)?

Acknowledgements The work reported in this paper was funded as part of the Low-Carbon After-Life (LoCAL) project under the European Commission Research Fund for Coal and Steel Grant RFCR-CT-2014-00001. The information on Shettleston is published by kind permission of the Shettleston Housing Association. We also wish to thank Dr. W. George Darling of the British Geological Survey for carrying out dissolved gas analyses from Caphouse and Markham (Table 1) and Drs Claire Wilson and Jaime Toney of the University of Glasgow for XRD analysis of ochre from Caphouse and Shettleston.

References

Abeliovich A (1985) Avoiding ochre deposits in soil drainage pipes. Agric Water Manage 10:327–334. doi:10.1016/0378-3774(85)90021-6

Athresh AP, Al-Habaibeh A, 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. Energy Procedia 75:1221–1228. doi:10.1016/j.egypro.2015.07.162

Athresh AP, Amin Al-Habaibeh A, Parker K (2016) The design and evaluation of an open loop ground source heat pump operating in an ochre-rich coal mine water environment. Int J Coal Geol 164:69–76. doi:10.1016/j.coal.2016.04.015

Bailey MT, Moorhouse AML, Watson I (2013) Heat extraction from hypersaline mine water at the Dawdon mine water treatment site. In: Tibbett M, Fourie AB, Digby C (eds) Proceedings of the conference "Mine Closure 2013", Eden Centre, Cornwall. Australian Centre for Geomechanics, UK, pp 559–570

Banks D (1997) Hydrogeochemistry of Millstone Grit and Coal Measures groundwaters, south Yorkshire and north Derbyshire, UK. Q J Eng Geol 30:237–256. doi:10.1144/GSL.QJEG.1997.030.P3.06

Banks SB (2007) The UK Coal Authority minewater-treatment scheme programme: performance of operational systems. Water Environ J 17(2):117–122. doi:10.1111/j.1747-6593.2003.tb00444.x

Banks D (2012) An introduction to thermogeology: ground source heating and cooling, 2nd edition. Wiley, Chichester, p 526

Banks D (2016) Making the red one green—renewable heat from abandoned flooded mines. In: Proc. 36th Annual Groundwater Conference, International Association of Hydrogeologists, Irish Group. "Sustaining Ireland's Water Future: The Role of Groundwater", 12th-13th April 2016, Tullamore, Co. Offaly, Ireland, Session VI, pp 1–9

Banks SB, Banks D (2001) Abandoned mines drainage: impact assessment and mitigation of discharges from coal mines in the UK. Eng Geol 60:31–37. doi:10.1016/S0013-7952(00)00086-7

Banks D, Younger PL, Arnesen RT, Iversen ER, Banks SB (1997a) Mine water chemistry: the good, the bad and the ugly. Environ Geol 32:157–174. doi:10.1007/s002540050204

Banks D, Burke SP, Gray CG (1997b) Hydrogeochemistry of coal mine drainage and other ferruginous waters in north Derbyshire and south Yorkshire, UK. Q J Eng Geol 30:257–280. doi:10.1144/GSL.QJEG.1997.030.P3.07

Banks D, Skarphagen H, Wiltshire R, Jessop C (2003) Mine water as a resource: space heating and cooling via use of heat pumps. Land Contam Reclam 11(2):191–198. doi:10.2462/09670513.814

Banks D, Skarphagen H, Wiltshire R, Jessop C (2004) Heat pumps as a tool for energy recovery from mining wastes. In: Gieré R, Stille P (eds) Energy, waste and the environment: a geochemical perspective, vol 236. Geological Society Publishing House, Bath, pp 499–513. doi:10.1144/GSL.SP.2004.236.01.27

Banks D, Fraga Pumar A, Watson I (2009) The operational performance of Scottish minewater-based ground source heat pump systems. Q J Eng Geol Hydrogeol 42:347–357. doi:10.1144/1470-9236/08-081

Banks D, Steven J, Berry J, Burnside N, Boyce A (2017) A combined pumping test and heat extraction/recirculation trial in an abandoned haematite ore mine shaft, Egremont, Cumbria, UK. Sustain Water Resourc Manag (**to be published**)

Bayless ER, Olyphant GA (1993) Acid-generating salts and their relationship to the chemistry of groundwater and storm runoff at an abandoned mine site in southwestern Indiana, USA. J Contam Hydrol 12(4):313–328. doi:10.1016/0169-7722(93)90003-B

Bracke R, Bussmann G (2015) Heat-storage in deep hard coal mining infrastructures. In: Proceedings World Geothermal Congress 2015, Melbourne, Australia, 19th–25th April 2015

Brown I, Goodchild J (1979) The coal mines of the Flockton area, near Horbury, West Yorkshire. Bull Peak Dist Mines Hist Soc 7(3):169–173. http://www.pdmhs.com/docs/default-source/bulletins/bulletin-7-3/bulletin-7-3—the-coal-mines-of-the-flockton-area-near-hor.pdf?sfvrsn=2. Accessed 10th Jan 2017

Burke T (1998) Report of the relationship of the proposed development at Glenalmond Street, Shettleston and nearby abandoned mine workings. Report 3.256 by Tom Burke Mining Consultant for Enconsult, January 1998

Burnside NM, Banks D, Boyce AJ (2016a) Sustainability of thermal energy production at the flooded mine workings of the former Caphouse Colliery, Yorkshire, United Kingdom. Int J Coal Geol 164:85–91. doi:10.1016/j.coal.2016.03.006

Burnside NM, Banks D, Boyce AJ, Athresh A (2016b) Hydrochemistry and stable isotopes as tools for understanding the sustainability of thermal energy production from a 'standing column' heat pump system: Markham Colliery, Bolsover, Derbyshire, UK. Int J Coal Geol 165:223–230. doi:10.1016/j.coal.2016.08.021

Burrows JE, Peters SC, Cravotta CA III (2015) Temporal geochemical variations in above- and below-drainage coal mine discharge. Appl Geochem 62:84–95. doi:10.1016/j.apgeochem.2015.02.010

Crook T (1912) On the frequent occurrence of ankerite in coal. Mineral Mag 16(75):219–223. doi:10.1180/minmag.1912.016.75.06

DOE (2015) Geothermal retrofit of Illinois National Guard's state headquarters Building. DOE award DE-EE0003002, Final Technical Report, 27th April 2015. 30 pp. doi:10.2172/1179248. http://www.osti.gov/scitech/biblio/1179248/. Accessed 4th May 2016

Dold B (2017) Acid rock drainage prediction: a critical review. J Geochem Explor 172:120–132. doi:10.1016/j.gexplo.2016.09.014

Dudeney B, Demin O, Tarasova I (2003) Control of ochreous deposits in mine water treatment. Land Contam Reclam 11(2):259–266. doi:10.2462/09670513.823

Eden RA, Stevenson IP, Edwards MA (1957) The geology of the country around Sheffield. Memoirs of the Geological Survey of Great Britain, Geological Sheet 100, Her Majesty's Stationery Office (HMSO), London

Faraldo Sanchez M (2007) Thermal balance of minewater treatment lagoons and wetlands. MSc thesis in Environmental Engineering, School of Civil Engineering and Geosciences, University of Newcastle, June 2007

Ferket HLW, Laenen BJM, Van Tongeren PCH (2011) Transforming flooded coal mines to large-scale geothermal and heat storage reservoirs: what can we expect? In: Rüde RT, Freund A, Wolkersdorfer C (eds), Proc. IMWA Congress 2011 (Aachen, Germany), Mine water—managing the challenges, pp 171–175

Grundl T, Delwiche J (1993) Kinetics of ferric oxyhydroxide precipitation. J Contam Hydrol 14(1):71–87. doi:10.1016/0169-7722(93)90042-Q

Gzyl G, Banks D (2007) Verification of the "first flush" phenomenon in mine water from coal mines in the Upper Silesian Coal Basin, Poland. J Contam Hydrol 92:66–86. doi:10.1016/j.jconhyd.2006.12.001

Gzyl G, Banks D, Younger PL, Głodniok M, Burnside N, Garzon B, Skalny A (2016). Low Carbon After-Life—overview and first results of project LoCAL. In: Drebenstedt C, Paul M (eds) Proc. IMWA conference 2016 (Leipzig, Germany), mining Meets water—conflicts and solutions, pp 593–599. http://www.imwa.info/imwaconferencesandcongresses/proceedings/298-proceedings-2016.html. Accessed Aug 2016

Hall A, Scott JA, Shang H (2011) Geothermal energy recovery from underground mines. Renew Sustainable Energy Rev 15:916–924. doi:10.1016/j.rser.2010.11.007

Hawkes L, Smythe JA (1935) Ankerites of the Northumberland coal-field. Mineral Mag 24(149):65–75. doi:10.1180/minmag.1935.024.149.03

Healeyhero (2015) Markham Colliery—1973. Background information—the colliery. HealeyHero website http://www.healeyhero.co.uk/rescue/pits/markham/markham_73_1.htm. Accessed 24th Oct 2015

INWATCO (2005a) Integrated Water Management In Former Coal Mining Regions: Guidance to Support Strategic Planning. Report available at http://www.wise-rtd.info/sites/default/files/d-2007-07-03-good_practice_guide.pdf. Accessed 24th May 2016

INWATCO (2005b) Integrated Water Management In Former Coal Mining Regions: Non-technical summary. http://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=home.showFile&rep=file&fil=LIFE02_ENV_UK_000140_LAYMAN.pdf. Accessed 24th May 2016

Janson E, Gzyl G, Banks D (2009) The occurrence and quality of mine water in the Upper Silesian Coal Basin, Poland. Mine Water Environ 28:232–244. doi:10.1007/s10230-009-0079-3

Janson E, Boyce AJ, Burnside NM, Gzyl G (2016) Preliminary investigation on temperature, chemistry and isotopes of mine water pumped in Bytom geological basin (USCB Poland) as a potential geothermal energy source. Int J Coal Geol 164:104–114. doi:10.1016/j.coal.2016.06.007

Jardón S, Ordóñez MA, Alvarez R, Cienfuegos P, Loredo J (2013) Mine water for energy and water supply in the Central Coal Basin of Asturias (Spain). Mine Water Environ 32:139–151. doi:10.1007/s10230-013-0224-x

Jessop A (1995) Geothermal energy from old mines at Springhill, Nova Scotia, Canada. In: Barbier E (ed) Proc. World Geothermal Congress 1995 (Florence, Italy, 18th–31st May 1995), International Geothermal Association, pp 463–468

Jessop AM, Macdonald JK, Spence H (1995) Clean energy from abandoned mines at Springhill, Nova Scotia. Energy Sources 17:93–106

Korb MC (2012) Minepool geothermal in Pennsylvania. Presentation at the 2012 PA AML Conference, New Frontiers in Reclamation, August 2nd-4th 2012, State College, Pennsylvania, USA. http://2012.treatminewater.com/KorbMinepoolGeothermal2012.pdf. Accessed 6th Feb 2016

Kruse N (2007) Simulation of hydrogeochemical processes in abandoned underground mines. PhD thesis, School of Civil Engineering and Geosciences, University of Newcastle, June 2007

Lake RD, Hough EH (ed) (2006) The Pennine lower and middle coal measures formations of the Barnsley district. British Geological Survey Internal Report, IR/06/135, p 47

Loredo J, Ordóñez A, Jardón S, Álvarez R (2011) Mine water as geothermal resource in Asturian coal mining basins (NW Spain). In: Rüde RT, Freund A, Wolkersdorfer C (eds), Proc. IMWA Congress 2011 (Aachen, Germany), mine water—managing the challenges, pp 177–181

Loredo C, Ordóñez A, Garcia-Ordiales E, Álvareza R, Roqueñia N, Cienfuegosa P, Peña A, Burnside NM (2017) Hydrochemical characterization of a mine water geothermal energy resource in NW Spain. Sci Total Environ 576:59–69. doi:10.1016/j.scitotenv.2016.10.084

Malolepszy Z, Demollin-Schneiders E, Bowers D (2005) Potential use of geothermal mine waters in Europe. In: Proceedings World Geothermal Congress 2005, Antalya, Turkey, 24–29 April 2005

Michel FA (2009) Utilization of abandoned mine workings for thermal energy storage in Canada. Proceedings Effstock 2009 Paper 105, Session 11_1. https://talon.stockton.edu/eyos/energy_studies/content/docs/effstock09/Session_11_1_Case%20studies_Overviews/105.pdf. Accessed Jan 2017

Minewater Project (2008) Minewater as a renewable energy resource: an information guide based on the Minewater Project and the experiences at pilot locations in Midlothian and Heerlen. The Minewater Project (INTERREG)

Nuenta (2015) Energy blade 3K4: energy blade installation instructions. Nuenta Ltd., Cannock. http://nuenta.com/viewproduct.asp?pid=109. Accessed 1st June 2016

Ordóñez A, Jardón S, Álvarez R, Andrésa C, Pendása F (2012) Hydrogeological definition and applicability of abandoned coal mines as water reservoirs. J Environ Monit 14:2127–2136. doi:10.1039/C2EM11036A

Precision Geothermal (2016) GeoCube™ website. http://precisiongeothermal.com/geocube.htm. Precision Geothermal LLC, Maple Plain, USA. Accessed 26th May 2016

Preene M, Younger PL (2014) Can you take the heat?—geothermal energy in mining. Mining Technol 123:107–118. doi:10.1179/1743286314Y.0000000058

Raftery A (2016) An assessment of ferrous iron oxidation, hydrolysis and precipitation as a function of temperature. MSc thesis in Hydrogeology, School of Geography, Earth and Environmental Sciences, University of Birmingham, August 2016

Ramos EP, Breede K, Falcone G (2015) Geothermal heat recovery from abandoned mines: a systematic review of projects implemented worldwide and a methodology for screening new projects. Environ Earth Sci 73:6783–6795. doi:10.1007/s12665-015-4285-y

Rostov Regional Government (2011) Новошахтинск согреют теплом шахтных вод (Novoshakhtinsk heats with warm mine water—in Russian). http://minjkh.donland.ru/Data/Sites/5/media/jkh/file/publikacii/innov.pdf. Accessed 6th Feb 2016

Sheppard TH (2005) A stratigraphical framework for the Upper Langsettian and Duckmantian of the East Pennine coalfields. British Geological Survey Internal Report IR/05/070. British Geological Survey, Keyworth, Nottinghamshire, UK

Tokarz M, Mucha W (2013) Wykorzystanie energii geotermalnej pochodzącej z odwadniania zakładów górniczych, na przykładzie rozwiązań zastosowanych w SRK S.A. Zakładzie CZOK w Czeladzi. Technika Poszukiwań Geologicznych 52:103–114

Tweedie S (2014) Maximising geoexchange performance with abandoned mines. In: Proc. 11th IEA Heat Pump Conference, 12–16 May 2014, Montreal (Quebec) Canada. Poster P.4.1. http://etkhpcorderapi.extweb.sp.se/api/file/1237. Accessed Jan 2017

Verhoeven R, Willems E, Harcouët-Menou V, De Boever E, Hiddes L, Op't Veld P, 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. doi:10.1016/j.egypro.2014.01.158

Watson I (2012) Dawdon mine water heat pump trial. Proc. IEA Heat Pump Programme Workshop, London 13th November 2012. http://web.ornl.gov/sci/ees/etsd/btric/usnt/03IWatson.pdf. Accessed 9th Feb 2016

Watzlaf GR, Ackman TE (2006) Underground mine water for heating and cooling using geothermal heat pump systems. Mine Water Environ 25:1–14. doi:10.1007/s10230-006-0103-9

Younger PL (2000) Predicting temporal changes in total iron concentrations in groundwaters flowing from abandoned deep mines: a first approximation. J Contam Hydrol 44(1):47–69. doi:10.1016/S0169-7722(00)00090-5

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 75 (2015) 1221 – 1228

Energy Procedia

The 7th International Conference on Applied Energy – ICAE2015

Innovative approach for heating of buildings using water from a flooded coal mine through an open loop based single shaft GSHP system

Anup P Athresh[a], Amin Al-Habaibeh[a]* and Keith Parker[b]

[a]*Innovative and Sustainnable Built Environment Technologies Research Group (iSBET)*
Nottingham Trent University, NG1 4BU, UK
[b]*Alkane Energy Plc, Edwinstowe House, Edwinstowe, Nottingham, NG21 9PR, UK*

Abstract

Geothermal energy, deep and shallow, has always been identified as an important renewable energy resource. The stable temperature and relatively low enthalpy of mine water contained in the abandoned and flooded coal mines have the potential to form a geothermal resource to be used in conjunction with heat pumps to provide heating and cooling for buildings. The usage of heat pump for space heating and cooling can be classified as a low carbon technology and if heat pump is powered by solar or wind energy it can be classified as a truly renewable technology. This paper presents a novel application of Ground Source Heat Pump (GSHP) for space heating and cooling using a flooded coal mine through an open loop based single shaft system. In this novel application, a single shaft is used for both extraction and injection of mine water for the heating application. This research work will report on the performance of the system and its long term potential in comparison to standard gas boilers heating systems. The usage of a single shaft system has been found effective in developing an efficient heating system with reduced cost and neutral environmental impact.

Peer-review under responsibility of Applied Energy Innovation Institute

Keyword: GSHP, Open loop, Mine water, Heat Exchanger, Low Carbon Technology

1. Introduction

Coal mining was in the past century one of the major industries in the UK and Europe where it played a key role in the economy of the nation as well as the communities in towns and villages surrounding the mines. When the mines were in operation, to make it safe for the workers, the underground galleries were kept dry by pumping the water out to maintain a safe working environment for the miners. With the

* Corresponding author. Tel.: +44 (0) 115 848 2564 .
E-mail address: Amin.Al-Habaibeh@ntu.ac.uk

Peer-review under responsibility of Applied Energy Innovation Institute
doi:10.1016/j.egypro.2015.07.162

closure the coal mines, pumping of water ceased and water has started to rise to the ground water level and most abandoned workings are now filled with low enthalpy water. This low enthalpy resource does not have much use for direct practical thermal applications. However heat pumps can be used to upgrade the low enthalpy water resource into a high enthalpy resource and to be used for heating and cooling of buildings.

Previous studies have described the process of harnessing the low enthalpy energy from coal mine water and using it for space heating and cooling applications through an open loop system. Examples of the concept of mine water application of heating and cooling and examples of working systems have been given [1] and [2]. The district heating at Herleen, Netherlands based on mine water has been described in [3]. Further details on usage of mine water based heating system around the world have been mentioned in [4]. The feasibility of mine water heating systems in Canada and USA has been mentioned in [5]. The feasibility of mine water based heating system at Coal Mining Museum at Wakefield has been discussed in [6]. Performance of a mine water based heating system in Scotland has been described in [7]. Reference [8] presents the recent developments in geothermal energy and the use of mine water for heating and cooling. The feasibility of mine water in heating and cooling in Spain has been outlined in [9].
The application GSHP for mine water and optimising the performance of the system through reliable system design requires availability of high quality data. This paper describes the system, instrumentation and data monitoring of a mine water based GSHP pilot plant at Alkane Energy control centre in Markham.

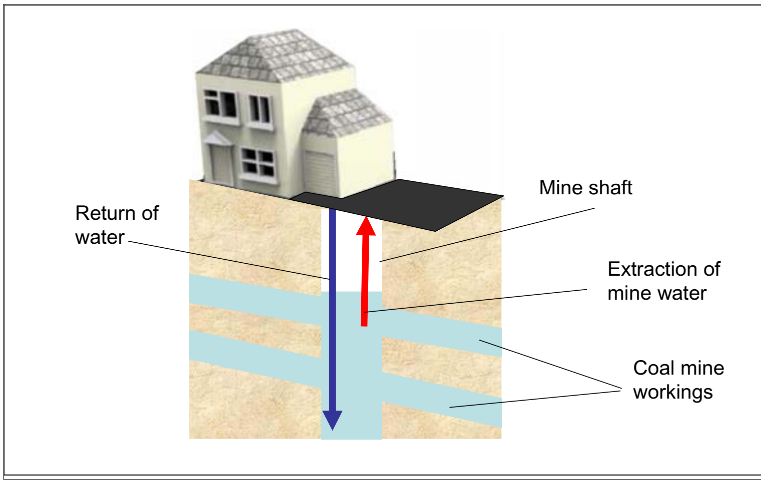


Figure 1: A schematic diagram of a single shaft coal mine GSHP system

2. Coal Mine Location

Markham Colliery was one of the largest collieries in UK and operated from 1905 until its closure in 1993. The underground galleries were accessed through four shafts present in the colliery complex. After the closure of the colliery three of the four shafts were filled, the No.3 shaft being left open to vent mine gas. This shaft was subsequently utilised by Alkane Energy to extract Coal Mine Methane (CMM) for the purpose of electricity generation. In 2006 the methane flow was cut off by the rising mine water sealing off the main roadway of inflow paths of methane to the shaft. Alkane Energy converted this site as their control centre and a maintenance depot, from where they could control all their operations across the various sites remotely. The water from the Markham Colliery shaft 3 is being used to heat all the office buildings of the Alkane Energy at Markham through a GSHP.

3. GSHP System

The GSHP system consist of a single 20 kW commercial Danfoss heat pump, counter flow shell and tube type heat exchanger, a 300 litre buffer tank, mesh filter and pipes connecting all the units. The borehole pump is installed in the mine shaft at a depth of 235 m below the ground level. The return hose of the borehole is at a depth of 250 m below the ground level. As a safety mechanism the methane in the mine shaft is monitored and would shut down the system if the methane level crosses a preset level.

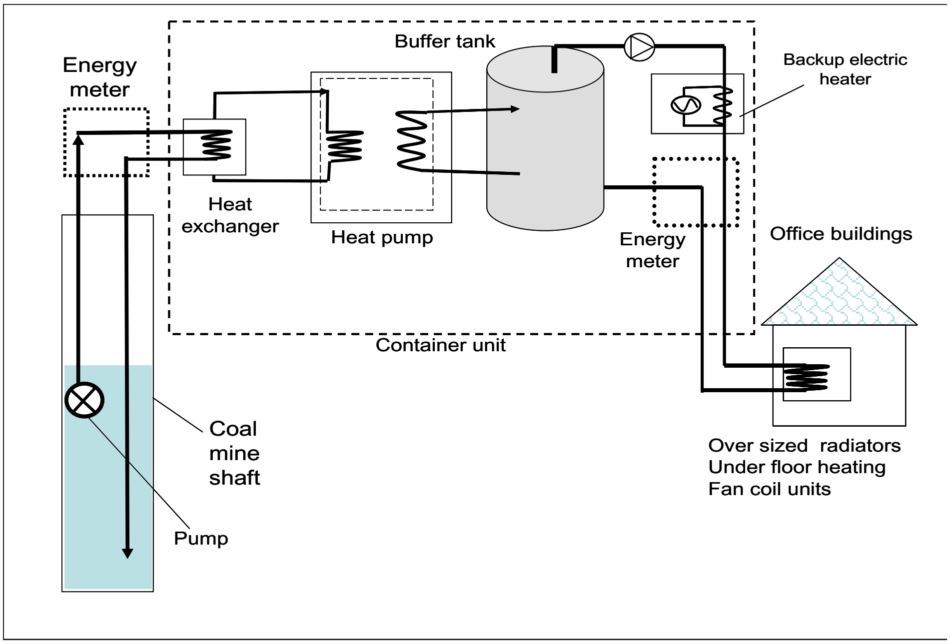


Figure 2: A simplified shematic system of the single shaft GSHP system at Markham, UK.

4. Instrumentation and Monitoring of the system.

The main parameters which need to be monitored are energy consumption and heat transfer rates between the mine water and the brine and these are determined by measuring the instantaneous fluid flow rate and out and return temperatures. Energy meters are installed to measure the electricity consumption of heat pump and mine pump. The SHARKY 775 heat meters are used to monitor the both the mine water and the heat pump output parameters. The heat meter measures the flow rate in m3/hr, ΔT of the water, instantaneous energy in kWh and cumulative energy in MWh. The SHARKY 775 consists of an integrated flow and temperature sensors and an integrator to calculate the energy based on the flow and temperature values. The entire monitoring system is coupled to telemetry and the data is continuously collected. Figure 3 presents some of the main parts of the instrumentation of the system.

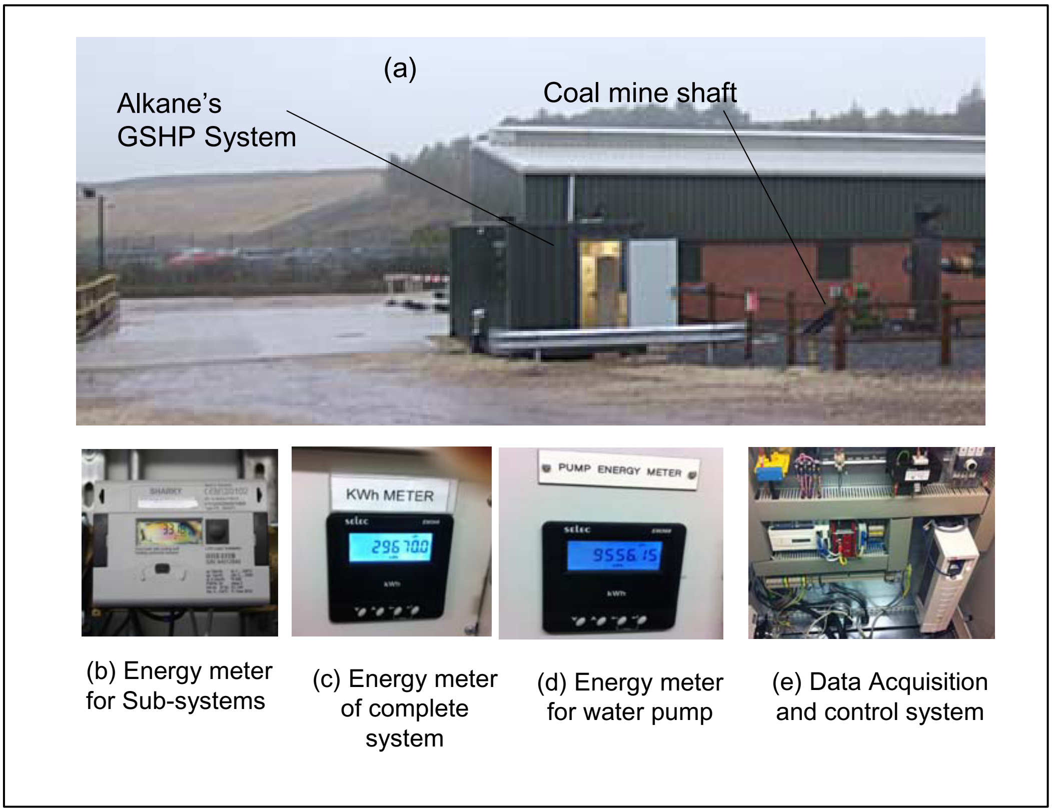


Figure 3: Alkane’s GSHP system (a), the energy meter for the coal mine water (b), the energy meter for the complete system (c), the energy meter for the water pump (d) and the data acquisition and control system (e).

5. Performance parameters

The efficiency of the GSHP system is measured in terms of COP (Coefficient of Performance). It is the main parameter of interest. It is defined as the ratio of the energy extracted by the heat pump to the electrical energy consumed by the heat pump. The amount of the energy extracted and consumed by the heat pump mainly depends upon the heat transfers between the mine water and brine, brine and evaporator of the heat pump and between condenser of the heat pump and building heat fluid. Figure 4 shows the difference in temperature between the extraction and return line of the mine water taken through using infrared thermography. COP of heat pump is the ratio between the energy produced and energy consumed by the system. The heat pump is the component in the system that extracts the energy from the coal mine water via heat exchangers, see Figure 2. The main components that consume electricity are the heat pump to power the circulation pumps and the compressor, in addition to the water pumps that pump the water from the coal mine and the circulate the water to the building. The consumption of the heat pump will depend on it design and the efficiency which is based on the input and output level of temperatures. The second aspect is the depth of the water in the coal mine and water flow rate since significant energy will be consumed to pump the water to ground level. Based on the system in consideration and its variables.

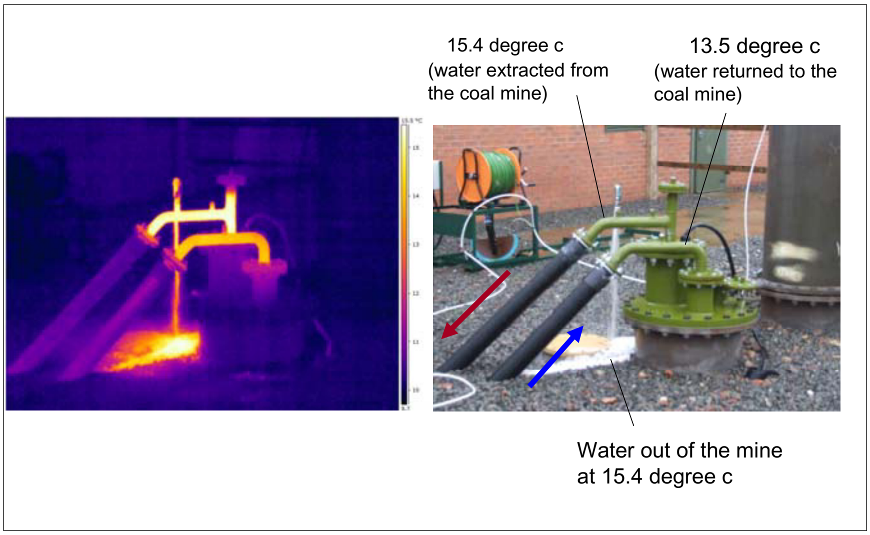


Figure 4: Infrared image of the extraction and return lines (left) and the corresponding visual image (right)

Figure 5 presents the relationship between the depth of water in Markham and its relationship with the COP values. At the depth of 120 meters, the COP value is about 2.7. This means for every 1KWh consumed by the system, 2.7 KWh is produced. The difference in energy is the energy extracted from the water in the mine. The water will sustain regulated temperature due to the geothermal energy and the significant volume of water in the coal mine. Due to the rising water level in the shaft, the COP is expected to reach a value of approximately of 3.95 at a depth of 15 meters. Figure 6 presents the relationship between the flow rate of coal mine water at depth of 235m and the COP of the system at different target output temperatures. It is evident that the increase in the flow rate will reduce the COP of the system for a given heating demand since no further energy will be extracted from the coal mine water. Also the increase in the target temperature will reduce the COP since the increase in temperature will increase the work needed by the heat pump to transfer the heat to a higher energy level.

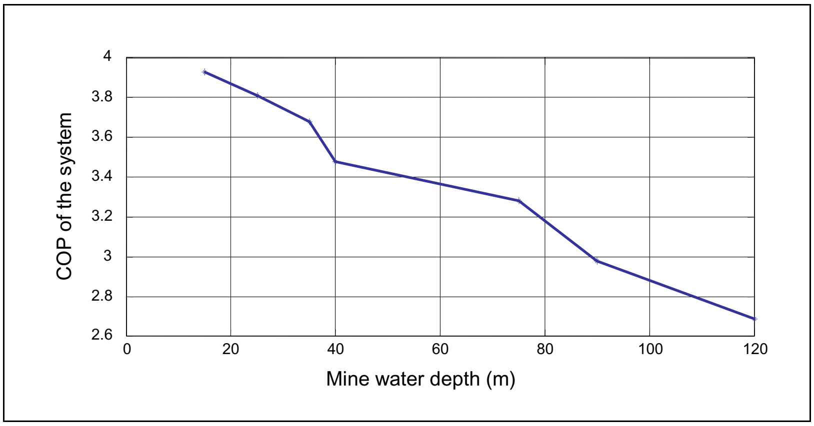


Figure 5: The relationship between the depth of water in the coal mine and COP of the system.

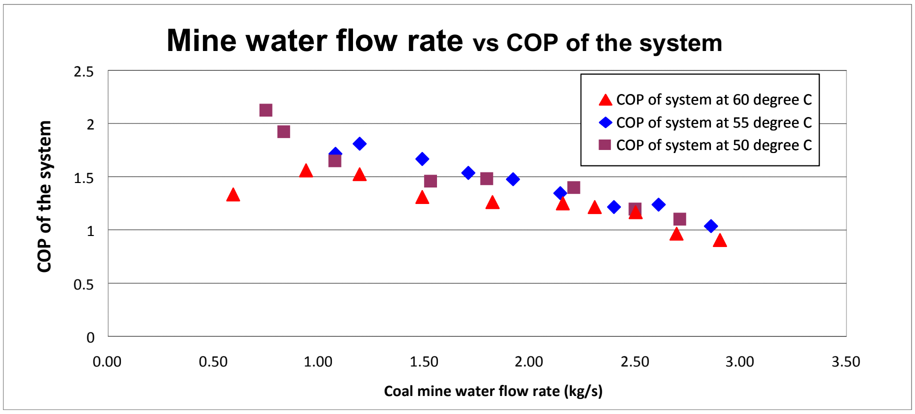


Figure 6: The relationship between mine water flow rate and COP of the system at different output temperatures (at water depth of 235m).

6. Conclusions

This paper has highlighted a novel application of for heating of buildings using water from a flooded coal mine through an open loop based single shaft GSHP system. It has been found that the COP of the system will depend on, *inter alia*, the depth of water in the coal mine, the flow rate of the water for a given heating capacity, and the target output temperature of the system. In comparison to a gas heater, the GSHP systems are much more efficient and produce much less carbon emission and consumes much less energy from the same heating demand. For example when compared with a modern boiler with 90% efficiency, the GSHP will produce 300% and 433% more energy for the same consumed energy for system COP of 2.7 and 3.9 respectively.

Acknowledgements

The authors would like to thank Innovate UK, Knowledge Transfer Partnership number 9032, for their funding of this research work.

References

[1] Banks, D., Skarphagen, H., Wiltshire, R. & Jessop, C. 2003. Mine water as a resource: space heating and cooling via use of heat pumps. Land Contamination and Reclamation 11(2), 191-198.
[2] Banks D. An introduction to thermogeology: ground source heating and cooling, 2nd edn, Oxford, Blackwell. 2012
[3] Roijen E, Op't Veld P, Demollin-Schneiders E (2007) The mine water project Heerlen – low exergy heating and cooling in practice. In: PALENC AIVC 2007.
[4] M. Preene, and P. L. Younger. "Can you take the heat? – Geothermal energy in mining." Mining Technology. 2014
[5] G. Wazlaf, T. Ackman,Underground mine water for heating and cooling using geothermal heat pump systems, Mine Water and the Environment, 25 (2006), pp. 1–14.
[6] Parker K. 2011. Potential for heat pumps in Yorkshire and the rest of the United Kingdom, in Heat pump technology using minewater, (ed. Faull M L), 32–42, Overton, UK, National Coal Mining Museum for England Publications.
[7] 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.
[8] A. Hall, J.A. Scott, H.L. Shang, Geothermal energy recovery from underground mines, Renew Sustainable Energy Rev, 15 (1) (2011), pp. 916–924.
[9] R. Rodríguez Díez and M. B. Díaz-Aguado, "Estimating Limits for the Geothermal Energy Potential of Abandoned Underground Coal Mines: A Simple Methodology", Energies 2014, 7(7), 4241-4260; doi:10.3390/en7074241.

Biography

Professor Amin Al-Habaibeh is a professor of Intelligent Engineering Systems within the Product Design team at Nottingham Trent University. He is currently leading the Innovative and Sustainable Built Environment Technologies research group (iSBET). Amin's interest also includes condition monitoring, intelligent systems, sustainable technologies, product design and advanced manufacturing technologies.

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 75 (2015) 1470 – 1476

Energy Procedia

The 7th International Conference on Applied Energy – ICAE2015

The design and development of an innovative simulator for an open loop system for extracting energy from flooded coal mines

Amin Al-Habaibeh*, Ben Meyerowitz, Duolan and Anup Athresh

Product Design, School of Architecture, Design and the Built Environment
Nottingham Trent University, Butrton Street, Nottingham, NG1 4BU, UK

Abstract

Water source heat pumps, in comparison to air-to-air heat pumps, have significant advantage for heating or cooling applications due to the relatively regulated temperature of most water resources. In the UK, similar to many other countries, disused coal mines have untapped potential for low cost green energy due to the flooding of coal mines with water at reasonable warm temperature due to the availability of geothermal energy at different depths. This allows to use water source heat pumps in locations away from rivers and seas for heating and cooling applications. Extracting energy from flooded coal mines using water heat pumps with open loop systems is still relatively a new concept, but can provide much heating capacity due to eliminating the time needed for heat transfer between the external environment and the heating loop in case of closed loop systems. The use of real systems to conduct research could be an expensive task or impractical to users of the application such as the residents of the served building. On the other hand, computer simulation includes significant assumptions that might not be accurate in many real situations. In this paper, the authors have developed a small scale simulator to help in understanding such energy systems and to conduct research in this field for the benefit of researchers, educators and students within the applied and renewable energy field. The paper describes the detailed design, the complete prototype and initial assessment of the system using infrared thermography and temperature monitoring. The results show that the system has been found successful in conveying the concept of extracting energy from coal mines and to characterize the general performance.

Peer-review under responsibility of Applied Energy Innovation Institute

* Corresponding author. Professor Amin Al-Habaibeh,
Tel.: +44(0) 115 848 2564;
E-mail address: Amin.Al-Habaibeh@ntu.ac.uk.

Peer-review under responsibility of Applied Energy Innovation Institute
doi:10.1016/j.egypro.2015.07.266

Keywords: coal mines, heat pumps, open loop, district heating, green energy,

1. Introduction

Despite the fact that UK is not actively volcanic, there is still a significant resource of geothermal energy available at different depths that could provide a clean and sustainable alternative to conventional domestic heating methods [1]. Ground energy source heating systems are considered to be one of the most energy efficient, environmentally sustainable and cost effective heating and cooling systems using the thermal store of the earth [2]. Ground source heating systems use a water source heat pump to extract heat from the ground and use it for heating or extract heat from buildings and dump it to the ground. Heat pumps are a simple concept that is used in almost every home as a 'refrigerator' or 'freezer' to extract heat from food and dump it externally. Air-conditioning systems are also a type of heat pumps that extract heat from buildings and dump it to the external environment. However, heat pumps for heating systems have been used more commonly in air-to-air heat pump systems to extract heat from the environment. Their drawback is, for heating purposes as an example, that the colder the weather and less efficient the processes becomes and hence the Coefficient of Performance (COP) becomes much less than expected. The 'efficiency' of a heat pump is measured by the Coefficient Of Performance (COP), which is the ratio between energy produced and the energy consumed by the system. A water source heat pump has relatively more stable COP because the temperature of the water source is not very sensitive to the change in outdoor air temperatures since the ground from which the heat is extracted has a more stable temperature. Figure 1 presents three configurations of water source heat pumps.

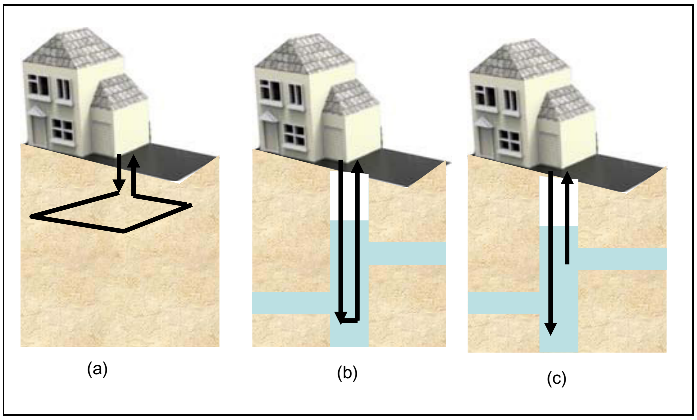


Figure 1: Three configurations for water source heat pumps, closed loop system ground source heat pump (a), closed loop energy from flooded coal mine (b) and open loop energy from flooded coal mine (c).

Configuration (a) presents the most common geothermal heating by using an underground closed loop where water is circulated to utilise the relatively stable temperature. Configuration (b) uses a closed loop system but uses the coal mine water as the media for heat exchange. This system is similar to configuration (a) but it enjoys much more efficient heat exchanging process since the closed loop is surrounded by water. Configuration (c) can be one of the most efficient configuration due to the fact the water itself from the coal mine is circulated in the system, hence a much larger capacity for heating can be utilised. This area of research in using water source heat pumps and disused coal mines has been attracting significant attention internationally; see for example [3-8]. This paper describes a novel system to simulate open loop coal mine heating system, configuration (c) of Figure 1, and its advantages and the results obtained from the initial testing.

2. The Design Idea

The first author through his research could not find a ‘user friendly’ energy from coal mine system at reasonable cost. Moreover, small scale water source heat pumps are relatively expensive and are not easily available. The initial idea of the novel approach is shown in Figure 2. The main idea is to use a simple portable fridge/freezer as a heat pump. Water will be circulated in the cold chamber, where food and drinks are stored in normal applications, to extract the heat. The extracted heat will be discarded by the condenser which will be utilized to heat a secondary circuit through a pipe coil with fins to transfer the heat to a small radiator inside a model of a house to simulate real life scenarios. Two pumps will be used, a large one to pump the water from the coal mine and the other one is used to pump the water in the closed circuit to exchange the heat between the heat pump and the house. An insulated chamber is used for the heat pump to enhance the heat transfer process between the condenser and the closed loop heating circuit.

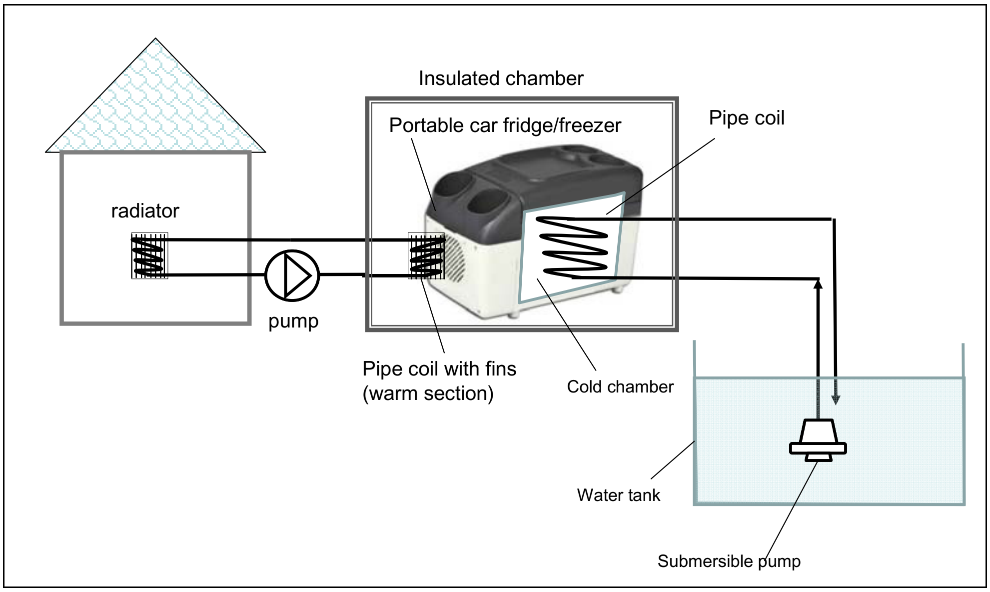


Figure 2: The novel concept of utilising mainly a portable fridge/freezer with a water tank to simulate the open loop coal mine heating system.

The design problem has been integrated as a product design brief which has been developed further by the MSc students at Nottingham Trent University in the product design team. To solve this problem, a practical but esthetically appealing system has been designed as shown by the CAD models in Figure 3. The design idea, as shown in Figure 2, is to develop a small scale system to simulate the configuration in Figure 1-c and Figure 2. With the lack of a reasonable low cost and small scale water source heat pump systems, the authors have used a small scale 12 volts car portable fridge/freezer and a fish tank as the two main components to simulate the system.

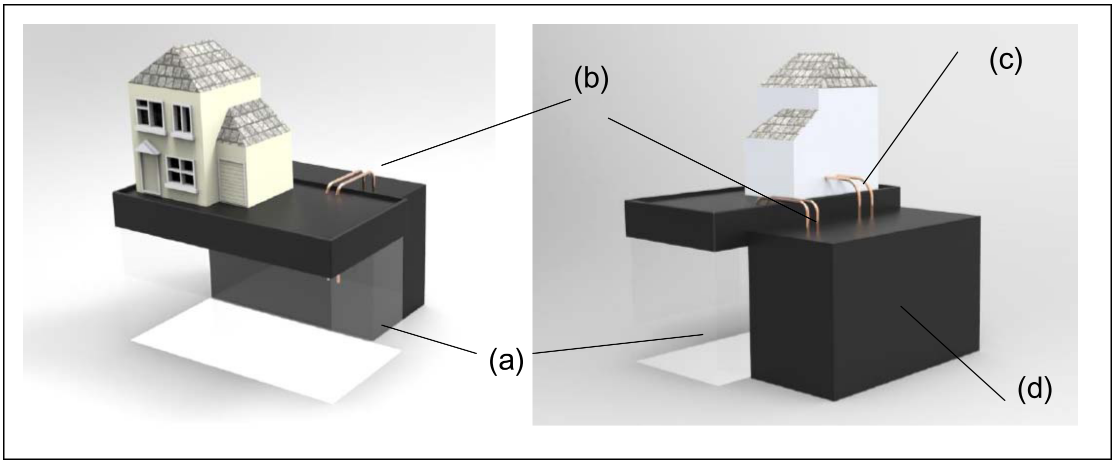


Figure 3: A 3D CAD model of the design systems; the water tank that simulates coal mine water (a), pipe from and to the coal mine (b), pipes from the heat pump to the house and vice versa (c) and the heat pump chamber (d).

Due to the relatively large scale of the portable fridge/freezer, the heat pump is integrated behind the water tank, see Figure 3. Figure 4 presents the actual system that has been developed and built which is almost identical to the initial design plan.

Figure 4: The complete novel design and built system based on the initial CAD model.

As presented in Figure 5, the heat pump is located behind the water tank with pipes attached to the cold chamber and the condenser.

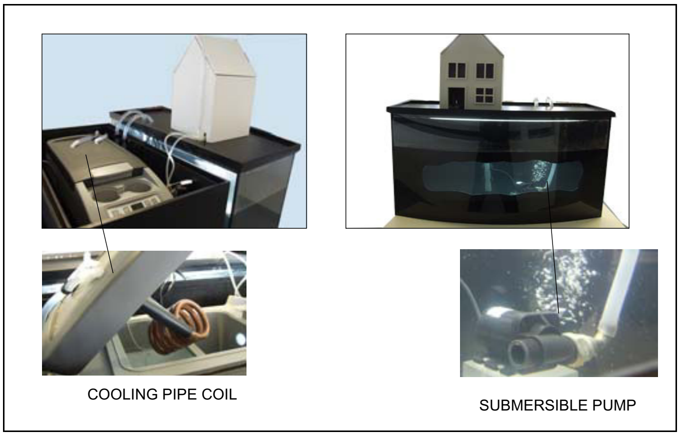


Figure 5: The novel system with the cooling pipe coil within the heat pump and submersible pump in the water tank.

3. Results and discussion

Figure 6 presents the results of the system using infrared thermography. It has been found clearly that the simulator is working as expected where the radiator in the house model has reached a temperature above 40 degree C while the water from the coal mine is at much lower temperature.

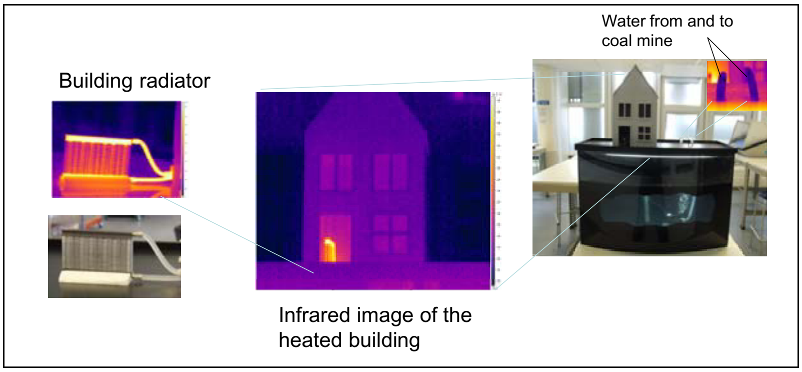


Figure 6: Results of the test using infrared thermography.

Figure 7 presented a temperature monitoring of the radiator, the water in the tank and the room temperature. Notice how the room temperature and the water tank temperature has been stable while the radiator temperature has reached a temperature of about 41 degree C. This heat has been extracted from the water tank through the heat pump. This model has provided a low cost opportunity for research as well as teaching applied energy concepts including energy from coal mines and heat pumps. People can 'feel' and 'see' the complete process which provides comprehensive understanding of the concept.

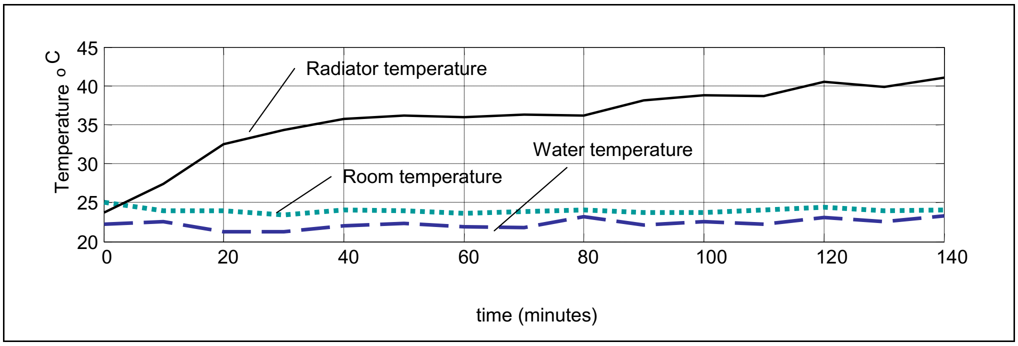


Figure 7: Comparison between room temperature, water temperature and radiator temperature.

4. Conclusions

This paper has presented a very successful and user friendly energy from coal mine physical simulator. The system can help in understanding the relationship between different variables at a very low cost and reduce development time. The simulator can be used for educational and teaching purposes. This work has been done as an integrated teaching and research project. Although the simulator has been found successful, further work is still needed. Calculation and improving COP is still on going work. To study and improve the COP, controlling the speed of the two pumps (i.e water flow rate) as well as improving the design of the heat exchangers are still needed to improve the performance and enhance energy efficiency. Future work will include also a fully automated and control system for full analysis, including the design of PWM and the effect of water height on the COP.

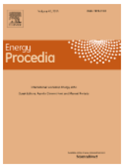
Acknowledgements
The authors would like to thank Innovate UK, Knowledge Transfer Partnership number 9032, for partially funding this work and Alkane Energy Plc for their collaboration. Also special thanks are due to the technical team at Nottingham Trent University, particularly Mr. Mark Beeston, for their support.

References

[1] Busby, J. (2013). Deep geothermal energy in operation. Available: http://www.bgs.ac.uk/research/energy/geothermal/home.html. Last accessed 23/04/2014.
[2] Rollin, K. (2010). Ground Source Heat Pumps - A Low-Carbon Energy Technology. Energy Resources. 12 (1), 10-19.
[3] Campbell, D. (2012). BGS expertise on the heat energy beneath Glasgow. Available:http://www.bgs.ac.uk/research/energy/geothermal/expertiseHeatEnergyGlasgow.html, accessed 30/10/2014.
[4] Verhoeven, R. Willems, E. (2013). 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 (1), 58-67.
[5] Hall, A. Ashley-Scott, J. (2011). Geothermal energy recovery from underground mines. Renewable and Sustainable Energy Reviews. 15 (2), 916–924.
[6] Karytsas, S. Theodoropoulou, H. (2012). Public awareness and willingness to adopt ground source heat pumps for domestic heating and cooling, Renewable and Sustainable Energy Reviews. 34 (1), 49–57.

[7] Luo, P. Chen, N. (2011). Abandoned coal mine tunnels: Future heating/power supply centers. Mining Science and Technology. 21 (5), 637–640.

[8] Watzlaf, G. Ackman, T. (2006). Underground Mine Water for Heating and Cooling using Geothermal Heat. Mine Water and the Environment. 25 (1), 1–14.



Biography

Professor Amin Al-Habaibeh is a professor of Intelligent Engineering Systems within the Product Design team at Nottingham Trent University. He is currently leading the Innovative and Sustainable Built Environment Technologies research group (iSBET). Amin's interest also includes condition monitoring, intelligent systems, sustainable technologies, product design and advanced manufacturing technologies.

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 105 (2017) 2531 – 2538

Energy Procedia

The 8th International Conference on Applied Energy – ICAE2016

An innovative and integrated approach for using energy from the flooded coal mines for pre-warming of a gas engine in standby mode using GSHP

Anup P Athresh[a,b], Amin Al-Habaibeh[a]* and Keith Parker[b]

[a]Innovative and Sustainable Built Environment Technologies Research Group (iSBET)
Nottingham Trent University, NG1 4BU, UK
[b]Alkane Energy Plc, Edwinstowe House, Edwinstowe, Nottingham, NG21 9PR, UK

Abstract

The effort to reduce energy consumption and carbon emission is driving companies to integrate multiple energy technologies to achieve the goal of reducing overall energy consumption, enhancing efficiency and decreasing operational cost. This paper outlines an innovative approach for integrating energy from flooded coal mines via a Ground Source Heat Pump (GSHP) to provide heating to buildings and at the same time to pre-warm a gas engine in standby mode. Once operational, the gas engine will produce significant waste heat that will replace the GSHP in heating the buildings. The results show that this energy integration technology provides much improved overall Coefficient of Performance and reduce carbon emission.

Peer-review under responsibility of the scientific committee of the 8th International Conference on Applied Energy.

Keyword: GSHP, Energy Integration, Low Carbon Technology, Gas Engines

1. Introduction

In the UK nearly half of all the energy is utilised for domestic and commercial heating and hot water requirements [1] and it costs the UK economy nearly £33 billion a year [2]. Currently only about 1 % of the heat generated is from renewable sources [3]. The UK is aiming to use renewable energy resources to provide nearly 12% of all the heating demand in the UK by the 2020 [4]. Flooded coal mines in the UK are a potential source of low enthalpy energy due to their availability all over the UK. Water from flooded coal mines is ideal to be used for heating and can greatly help in meeting the target of sourcing 12% of

* Corresponding author. Tel.: +44 (0) 1158482564.
E-mail address: Amin.Al-Habaibeh@ntu.ac.uk

Peer-review under responsibility of the scientific committee of the 8th International Conference on Applied Energy.
doi:10.1016/j.egypro.2017.03.726

heating demands from renewable energy and reduce carbon footprint. The energy sourced from wind is not always available and difficult to predict on the long term; at the same time without energy storage, solar energy will not be available at night. As the reliance on renewable energy is increasing, it is also necessitating the need to have a backup, mainly internal combustion engine generators as they can be pressed into service quickly to meet the demand. However, gas and diesel engines, particularly in winter, require heating when they are on standby to allow rapid start and reliable operation. Figure 1 presents an example of UK electricity demand during 24 hours period on 11 January 20016, a typical winter day in the UK. The demand peaks in the afternoon between about 4 PM and 7 PM. When this peaks occurs at low wind speed, stand by gas engines will start their operation to compensate for the high demand. This paper presents a novel and new approach on how a GSHP system is be used to pre-heat a standby gas generator, so that it can be readily started as and when there is a demand for electricity owing to demand and supply mismatch from the national grid. Other advantage of this system is to partially recover the waste heat from the cooling system of the engine and use it to provide the required heating for buildings.

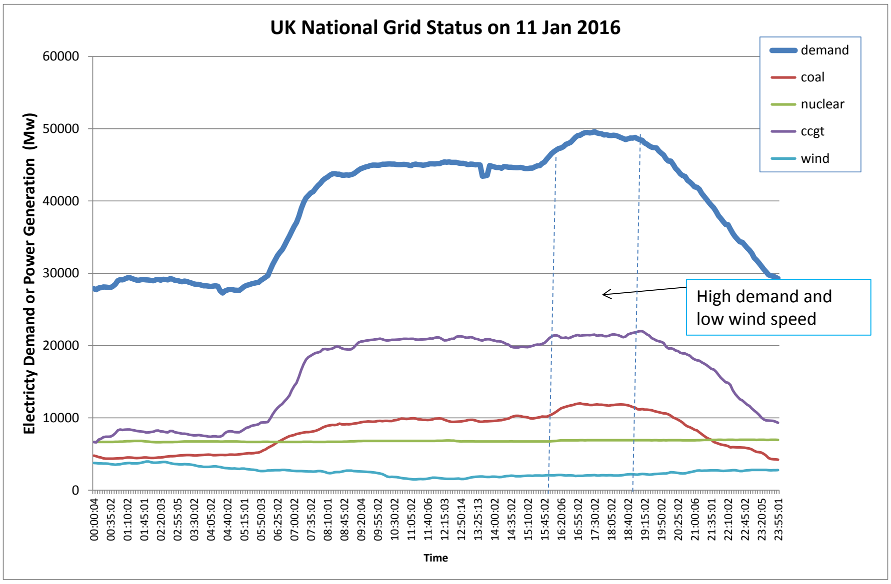


Figure 1: An example of UK electricity instantaneous demand and supply data on 11 Jan 2016, (data source: [5]).

2. Energy Recovery From Flooded Coal Mines Using Heat Pumps

There was a widespread closure of collieries in the UK and in Europe towards the end of the 20th century. When the collieries were active, and in order to safely extract coal from the underground seams, water had to be continuously pumped out. Once the mines closed the pumping operations ceased. This stoppage had led to the recovery of water level to water table level and therefore most of the mines are now flooded [6,7]. The application of mine water for heating and cooling applications has been well known for quite some time, but still not many installations have been documented, as of 2013 only 20 were documented [8].

A detailed description of heat pumps principle of operation, types and configurations has been mentioned in [9-11]. The latest trends in the heat pump technology has been also described in reference [12]. The models to estimating the amount of thermal energy that can be recovered from flooded coal mines has been described in references [13-15]. The details of the various mine water based heating and cooling installations around the world has been described in [8,16-18]. Reference [19] describes a novel simulator to teach and understand the technology in detail in a lab environment. A pilot mine water heating and cooling scheme has been successfully implemented in the Dutch town of Herleen and the details of this scheme has been described in [20, 21].

The efficiency of a heat pump is measured in terms of COP (Coefficient of Performance). It is the main parameter of interest. It is the ratio between the thermal energy output of the heat pump and the electrical energy consumed by the heat pump. The amount of energy produced and consumed by the heat pump mainly depends upon the heat transfers between the mine water and brine, brine and evaporator of the heat pump and between the condenser of the heat pump and building's heating fluid. The COP of the system is measured as a ratio of the thermal output of the system to the energy consumed by the system. This includes electricity consumed by the mine pump in addition to the heat pump. When the gas engine is in operation, there will be no need to run the heat pump and the waste heat from the engine will be used for heating the buildings.

In mathematical terms:

Energy that can be extracted from the mine water is calculated using equation 1.

$$Q_{mw} = m_{mw}.C_p.\Delta T \quad kJ \tag{1}$$

Where:

Q_{mw} is the thermal energy of mine water in kJ, m_{mw} is mass of mine water in kg, C_p is the specific heat of water (4.18 kJ/kg.K) and ΔT is the difference in temperature in Kelvin.

Efficiency or COP of the heat pump is calculated using equation 2.

$$COP_{Heatpump} = \frac{Thermal\ Energy\ produced\ by\ the\ heat\ pump\ in\ kJ}{Electrical\ Energy\ consumedby\ the\ heat\ pump\ \ in\ kJ} \tag{2}$$

$$\mathrm{COP}_{Heatpump} = \frac{Q_{HP}}{W_{HP\ electrical}} \tag{3}$$

Where
$W_{HP\ electrical}$ is the electrical power consumption of heat pump in kJ, Q_{HP} is the thermal energy output produced by the heat pump in kJ

Efficiency or COP of the system includes the energy consumed by the heat pump, mine water pump and the circulation pump and it is calculated using equation 4.

$$COP_{system} = \frac{Thermal\ Energy\ produced\ by\ system\ in\ kJ}{Electrical\ Energy\ consumed\ by\ system\ in\ kJ} \tag{4}$$

$$COP_{system} = \frac{Q_{HP}}{W_{HP\ electrical} + W_{MP\ electrical} + W_{CP\ electrical}} \quad (5)$$

The modified efficiency or COP of the system includes the energy recovered from the engine in addition to the thermal output of the heat pump and is calculated using equation 6.

$$COP_{modified} = \frac{Q_{HP} + Q_{recovered}}{W_{HP\ electrical} + W_{MP\ electrical} + W_{CP\ electrical}} \quad (6)$$

Where

$W_{CP\ electrical}$ is the electricity consumed by the circulation pumps in kJ and $Q_{recovered}$ is the thermal energy recovered from the waste heat of the engine.

3. Overall system description

The mine water heat recovery system under discussion has been used to heat the buildings described in detail in reference [22]. Figure 2 shows an image of the Markham site where the system is installed. The heating from this GSHP has been modified to pre-warm the gas engine in standby mode and then recover the waste heat from the engine when it is in operation. The overall system, see reference [22], consists of pumping the lukewarm water from the existing mine shaft of former Markham colliery and is the passed through a shell and tube heat exchanger, where a part of the energy from the incoming mine water is extracted by the cooler brine coming from heat pump. Then the cooled mine water is injected back to the coal mine, while the warmer brine is pumped back to the heat pump.

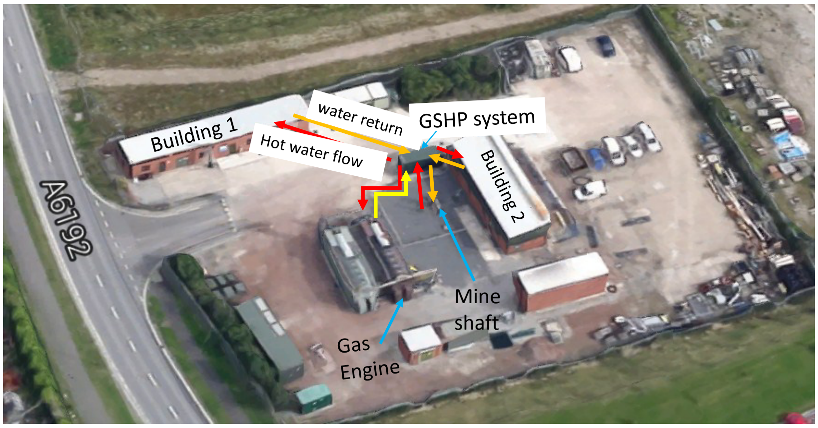
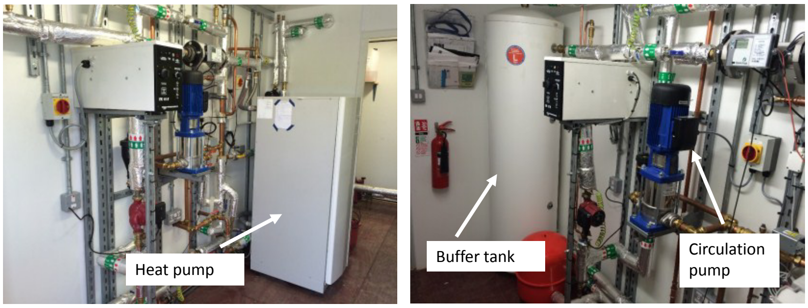


Figure 2: A satellite image of the GSHP system site (source: [23])

The heat pump in this situation upgrades the lukewarm water with its low grade energy of the brine into a more useful high temperature high grade energy; where this high temperature water is pumped into a buffer tank. The buffer tank stores the high temperature water, from where it is circulated around the building and also the engine to keep it warm and ready for operation in cold weather. The buffer tank not only ensures the supply of constant temperature water, but also prevents frequent cycling of the compressor and thereby increasing the efficiency and life of the compressor of the heat pump.



(a) (b)

Fig. 3. A picture showing the heat pump (a), and the buffer water tank with the circulation pump (b).

Figure 3 presents the heat pump system which includes the heat pump Figure 3-a and buffer tank Figure 3-b. Further details about the system can be found in [22].

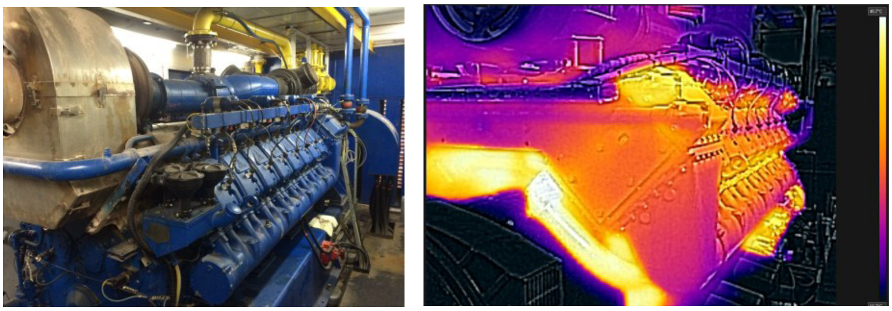
(a) (b)

Fig. 4. The gas engines on the site (a), and the infrared image of the system showing the significant heat produced during operation (b).

Figure 4 shows two gas engines on the site. The gas engines are used as a STOR (Short Term Operating Engine) generation. Whenever there is a demand or supply mismatch, National Grid, the main electricity transmission and distribution company in UK tries to balance electricity supply and demand by procuring additional power from the independent generators such as Alkane Energy at a short notice. Alkane Energy uses gas engines to supply the additional electricity and in order to start the engine quickly, the engines have to be pre-warmed. For this innovative work, one of the engines has been linked to GSHP to improve COP and efficiency.

4. Results and Discussions

Figure 5 shows the gas engine during operation and the heat generated using an infrared image. Figure 6-a shows a schematic of the GSHP system in heating mode, where the GSHP system is heating the building and the engine in standby mode. Figure 5-b shows when the engine is running and a part of the waste heat from the engine is recovered and is stored in the buffer tank in the form of hot water, which is then circulated around the building, thereby removing the need to switch on the heat pump and mine pump, resulting in higher COP values.



(a) (b)

Fig.5. The gas engine with heating system installed (a) and infrared image of the preheated engine on stand by (b).

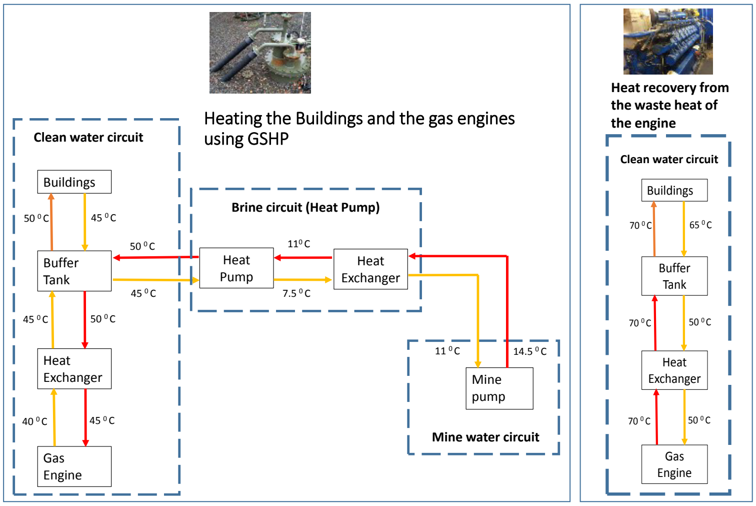


Fig. 6. A schematic block diagram of heating using GSHP (a) and a schematic block diagram of waste heat recovery (b).

During the winter period when the demand for heat is at its maximum, the gas engine runs at least for a minimum period of four hours daily. When the gas engine is running, the heat from engine's cooling jacket is used for heating the buildings. Excess heat during the engine's operation is stored in the buffer tank as hot water and this hot water is circulated around the building for heating for many hours even after the engine is switched off. Thus, removing the need to switch on the heat pump or the coal mine pump. In this case, only the circulation pumps will be needed to circulate the hot water between the building and the engine via the buffer tank. By recovering the heat from the engine's cooling jacket and using it in conjunction with the GSHP, the overall COP of the system increases by at least 25% in this case.

5. Conclusions

The global requirements to control carbon emission has led to closing down many traditional coal based power stations and replacing them with solar and wind renewable energy plants. This has necessitated the need to have a quick backup energy sources to compensate for the demand and supply fluctuations. This provides the opportunity to combine multiple technologies and thereby maximising the renewable energy produced. This paper has highlighted an innovative approach of coupling of multiple technologies together to reduce the operational costs and maximising the benefits of using more sustainable technologies. GSHP has been found useful when integrated with backup gas engines to provide an improve heating systems with reduce carbon emission and reduce cost.

Acknowledgment
This paper is based on field research carried out within the frame of research project: Low-Carbon After-Life (LoCAL) financed by the European Commission, Research Fund for Coal and Steel, July 2014 - June 2017 (Contract No.: RFCR-CT-2014-00001).

6. References

[1] DECC UK, The future of heating: Meeting the challenge, 2013.
[2] DECC UK, The Future of Heating: A Strategic Framework for Low Carbon Heat in the UK, 2012.
[3] Connor PM, Xie L, Lowes R, Britton J, Richardson T. The development of renewable heating policy in the United Kingdom, Renewable Energy, 2015 Mar 31;75:733-44.
[4] DECC UK, The UK Renewable Energy Strategy, 2009.
[5] Gridwatch, www.gridwatch.templar.co.uk/download.php , accessed on 20 June 2016.
[6] Henton MP, The problem of water table rebound after mining activity and its effect on ground and surface water quality, Studies in Environmental Science, 1981 Dec 31; 17:111-6.
[7] Young PL, The longevity of minewater pollution: a basis for decision-making, Science of the Total Environment, 1997 Feb 24; 194:457-66.
[8] Preene M, Younger P. , Can you take the heat?-Geothermal energy in mining, Min Technol 2014;123(2):107-118.
[9] Watzlaf GR, Ackman TE., Underground mine water for heating and cooling using geothermal heat pump systems, Mine Water and the Environment 2006; 25(1):1-14.
[10] Banks D., Skarphagen H, Wiltshire R, Jessop C. , Heat pumps as a tool for energy recovery from mining wastes, Geological Society, London, Special Publications 2004; 236(1):499-513.
[11] Banks D., An introduction to thermogeology: ground source heating and cooling, John Wiley & Sons, 2012.
[12] Chua K, Chou S, Yang W., Advances in heat pump systems: A review, Applplied Energy, 2010; 87(12):3611-3624.
[13] Rodríguez R, Díaz MB., Analysis of the utilization of mine galleries as geothermal heat exchangers by means a semi-empirical prediction method, Renewable Energy, 2009; 34(7):1716-1725.
[14] Madiseh SG, Ghomshei MM, Hassani F, Abbasy F., Sustainable heat extraction from abandoned mine tunnels: A numerical model, Journal of Renewable and Sustainable Energy, 2012; 4(3):033102.
[15] Andrés C, Ordóñez A, Álvarez R. Hydraulic and Thermal Modelling of an Underground Mining Reservoir, Mine Water and the Environment, 2015:1-10.
[16] Hall A, Scott JA, Shang H. Geothermal energy recovery from underground mines. Renewable and Sustainable Energy Reviews, 2011;15(2):916-924.

[17] Ramos EP, Breede K, Falcone G., Geothermal heat recovery from abandoned mines: a systematic review of projects implemented worldwide and a methodology for screening new projects, Environmental Earth Sciences, 2015; 73(11):6783-6795.
[18] Athresh AP, Al-Habaibeh A, Parker K., The design and evaluation of an open loop ground source heat pump operating in an ochre-rich coal mine water environment, International Journal of Coal Geology, 2016.
[19] Al-Habaibeh A, Meyerowitz B, Athresh A., The design and development of an innovative simulator for an open loop system for extracting energy from flooded coal mines. Energy Procedia, 2015 Aug 31; 75:1470-6.
[20] Roijen E, Op't Veld P, Demollin-Schneiders E., The Minewaterproject Heerlen-low exergy heating and cooling in practice, PALENC AIVC, 2007.
[21] Verhoeven R, Willems E, Harcouët-Menou V, De Boever E, Hiddes L, Op't Veld P, et al. 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 2014;46:58-67.
[22] Athresh AP, Al-Habaibeh A, Parker K. Innovative Approach for Heating of Buildings Using Water from a Flooded Coal Mine Through an Open Loop Based Single Shaft GSHP System. Energy Procedia 2015;75:1221-1228.
[23] Google maps, www.google.co.uk/maps, accessed on 20 June 2016.

Biography

Professor Amin Al-Habaibeh is a professor of Intelligent Engineering Systems at Nottingham Trent University. He is currently the Director of the Doctoral Training Alliance for Energy (DTA-Energy) within the UK University Alliance universities. Amin is also leading the Innovative and Sustainable Built Environment Technologies research group (iSBET). Amin's interest includes, in addition to energy, condition monitoring, intelligent systems, sustainable technologies, product design and advanced manufacturing technologies.