Geothermal prospects in the United Kingdom, current and future

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1. Introduction

Geothermal energy uses the heat within the Earth's crust to generate electricity and provide heat. It is generally considered to be one of the cleanest energy resources available as it leads to minimal carbon emissions. It also presents advantages against other renewables as it is a continuous form of energy that is independent of the time of day or the weather. Geothermal energy is not restricted to volcanic areas, as is often assumed. In fact, geothermal energy can be developed in a variety of settings: deep geothermal power plants in non-volcanic areas, hot water extraction from deep aquifers for direct heat use, and shallow geothermal applications for heat extraction and storage. All these geothermal uses require different technologies depending on their location.

The first aim of this report is to clarify the differences between geothermal technologies and to specify which can be used in the United Kingdom. The geothermal sector has not grown in the UK as it has in other European countries like France or Germany over the last few decades. This report summarizes the factors that have led to this impeded growth and looks at different scenarios to investigate how this might change over the next 30 years. Finally, policy recommendations are suggested that will help with the development of the geothermal industry in this country.

2. What is geothermal energy?

Geothermal technologies can be classified into three broad types: power generation, direct heat use from deep geothermal resources (>100 metres) and Ground Source Heat Pumps (GSHPs) from shallow geothermal resources (<100 metres). In order to clear up some of the misunderstandings around the different geothermal technologies, we provide a brief description of each technology and its applications.

2.1. Power Generation

Power generation is the technology most widely associated with geothermal use on a global scale and images of steaming ground and geysers in Iceland often come to mind. Current technologies only enable us to produce electricity from geothermal resources in very specific locations in the world.

The most common and well-developed geothermal resources are those found in volcanic areas (Table 1). In these areas, super-heated steam circulates at relatively shallow depths within the Earth's crust (1,000-5,000 metres beneath the surface) through natural fractures, created by the tectonic movements inherent with volcanic systems. The steam is tapped and used to power turbines that generate electricity. These resources are often referred to as "high enthalpy" resources, which means that they are high temperature-high pressure systems (steam >180°C) that have a high potential of producing power.

Power generation is also developed in less conventional areas such as Hot Sedimentary Aquifers (HSAs) (Table 1). These are deep porous sedimentary reservoirs that contain heated water (70-180°C) and are referred to as "low" or "medium enthalpy" resources depending on their temperature. The water is not hot enough to vaporise into steam so binary power plant technology is used to produce electricity. Binary power plants pass the hot water from the HSAs through a heat exchanger, which heats up a secondary, organic fluid with a lower boiling temperature. This secondary fluid is vaporised and compressed to power the turbines (IEA, 2010). Examples of binary power plants that use this technology are Organic Ranking Cycle (ORC) or Kalina cycle power plants.

Enhanced Geothermal Systems (EGS) constitute the latest geothermal power generation technology to have been developed. It is still at a demonstrator level, with a pilot power plant installed at Soultz-sous-Forêts, France, with capacity of 2.2 mega-Watt electricity (MWe) (Table 1). EGS technology aims to enhance the productivity of a reservoir by fracturing the reservoir rock and enabling fluid circulation, leading to higher flow rates. This pioneering technology has been investigated both in "Hot Dry Rock" systems (HDR) and in Hot Sedimentary Aquifers (HSAs). HDR systems use deep granitic rocks, which are particularly interesting for geothermal use because they have a high heat flow due to their inherent radioactivity. Granitic rocks are crystalline and non-porous however so they do not enable fluid flow. Fracturing the granite enables water to flow through the hot rock, which is then heated up and extracted to power a binary power plant. EGS in HSA settings is used to fracture the porous sedimentary rock to enhance the fluid flow through the reservoir and increase its productivity. The Soultz-sous-Forêts power plant in France is in an HSA setting.

Table 1 – Summary of the difference geothermal technologies

Geothermal technology	Commercial status	Location
Conventional resources		
Volcanic systems	Commercial (>90% installed capacity)	USA, New Zealand, Indonesia, Philippines, Mexico, Iceland, Italy, Kenya, Japan
Unconventional resources		
Hot Sedimentary Aquifers – binary power plants	Commercial (<10% installed capacity)	Germany, USA
Enhanced Geothermal Systems (EGS)	Demonstration	France, Germany, Japan, USA, Australia

Souce: IME, 2013; Cladouhos et al., 2010

2.2. Direct geothermal heat use

Geothermal resources are used directly in the form of hot water for a number of applications: space and district heating, water heating (spas, swimming pools…), aquaculture (fish farms), horticulture (growing crops in greenhouses, drying crops…) and industrial processes (pasteurizing milk…) (IEA, 2010). Amongst the countries that use direct geothermal heat are Iceland, Japan, Turkey, New Zealand, Germany, France, Italy and Hungary (Lund and Boyd, 2015).

Direct geothermal heat use has great potential because it can use any reservoir, volcanic or sedimentary, provided the water is at a high enough temperature for direct use. Direct heat can be extracted from the geothermal power plant waste water. For example in Iceland, the waste water from the Hellisheiði power plant is redistributed through a district heating network and provides space heating for the majority of the capital, Reykjavik, and neighbouring towns. This is an example of an energy cascade (a chain of energy uses from high temperature to low temperature), which demonstrates the great potential for energy efficiency of well-designed geothermal resources.

Direct use of geothermal resources have geographical constraints however as they are most useful when exploited near areas with high heat density (i.e. cities and towns) as heat cannot be efficiently transported over long distances.

2.3. Ground Source Heat Pumps

Whereas the two geothermal technologies described above use energy from considerable depth within the Earth's crust, Ground Source Heat Pumps (GSHPs) function with the energy stored at shallow depth within the Earth (<100m). Although the heat present at this depth technically comes from the solar energy heating of the ground, this technology is also generally referred to as geothermal energy (IEA, 2010).

GSHPs transfer the heat to or from the ground, using the Earth as a heat sink in the summer or as a heat source in the winter. In a winter scenario, fluid flows through an underground pipe system, absorbing heat from the subsurface. It then passes through the heat pump where is transmits the absorbed heat to the working fluid (air or water), which provides space heating or domestic hot water. In the summer, the scenario is reversed, resulting in sustainable system.

This technology is popular in the United States, China, Sweden, Germany and France (Lund and Boyd, 2015). In Sweden, GSHPs provide 17.5 TWh of renewable heating, making Sweden the world's third leading country in geothermal energy utilisation (Gehlin and Andersson, 2016).

2.4. Advantages and drawbacks of geothermal energy

The impacts on our environment of green house gas (GHG) emissions from fossil fuels used for conventional power production, heating and transport are becoming clearer and there is a global drive to develop a more varied energy mix and prioritise the use of renewable energies. This global effort was demonstrated at the COP 21 in Paris in December 2015 where 194 countries agreed a common goal to limit global temperature increase well below 2°C (C2ES, 2015). The Global Geothermal Alliance, launched during the COP 21 summit, aims to increase the share of geothermal energy in the global energy mix (IRENA, 2015).

Geothermal has an important role to play in helping to reduce global GHG emissions. The Geothermal Energy Association (GEA) estimates that geothermal power plants emit 5% of the carbon dioxide, 1% of the sulphur dioxide and <1% of the nitrous oxide produced by a coal-fired plant of equal size (Holm et al., 2012). In the UK, geothermal power plants are likely to be binary power plants that use closed loop systems in which extracted fluid is re-injected into the ground and as a result they produce near-zero emissions. Moreover, there are no carbon emissions associated with fuel transport. In terms of direct heat use and GSHPs, the carbon emissions depend on the CO_2 intensity of the electricity used to power the heat pumps. In the UK, the use of heat pumps for individual and district heating would reduce the carbon emissions significantly by diverting heat production away from individual gas boilers.

Geothermal energy is also a reliable, predictable and secure source of energy. It has the ability to produce continuous power and heating irrespective of the time of day, season or the weather, unlike wind or solar energy. Concerns over reservoir depletion have led to sustainable practices to be developed at geothermal power plants, whereby the fluids are not extracted from the ground at a higher rate than they are replaced. When managed this way, geothermal energy is a sustainable resource (IEA, 2010). Geothermal energy provides a local and decentralized source of energy, which provides greater energy security. Finally, once installed a geothermal plant has low running costs, as it does not require fuel (IEA, 2010).

All forms of energy production have drawbacks and geothermal energy is no exception. Firstly, the high initial costs and high risk associated with building a power plant can make geothermal unattractive to investors. This challenge can be overcome, however, if carbon emissions are taken into account in the cost of energy production. This brings the cost of geothermal down considerably. Secondly, as with all underground operations, there is a risk of pollution from the geothermal fluids. Geothermal fluids come from great depth within the Earth's crust and are often very saline and contain trace elements such as lead or zinc (GEOCOM, 2012). Great care is taken during the drilling stage to avoid contamination of ground water aquifers or surface water reservoirs. Boreholes are cased and sealed to avoid leakages. In the UK, surface water is unlikely to be contaminated by waste water disposal because the power plants would operate with a closed loop system, in which the fluids are re-injected into the ground. Finally, drilling into the Earth's crust and extracting fluid from reservoir can lead to small amounts of seismicity. In conventional geothermal operations, this risk does not exceed the risk of seismicity associated with other routine underground engineering operations, such as in mining or oil and gas operations. There is a higher risk of seismicity however associated with EGS. The injection of fluids into the ground to fracture the rock can lead to unexpectedly large seismic events, such as in Basel, Switzerland, where several events greater than magnitude 3 were felt in the area in 2006, following the injection of fluids into the well (Haring et al., 2008; Cladouhos et al., 2010). Induced seismicity is also a common problem in hydraulic fracturing of shale in the oil and gas industry. A lot of current research in both the shale gas and the geothermal industries is focussed on understanding stress changes in the subsurface and how to mitigate induced seismicity. So as EGS technologies mature, project developers should have a better understanding of how best to avoid large seismic events.

3. Geothermal in the UK

3.1. Historic use of geothermal in UK

The first geothermal resources that were used in the UK were the hot springs. These were used principally for bathing, religious and health purposes. The most famous early geothermal resources in the UK are the Roman Baths in Bath, where the Romans built a temple and bathing complex in the first century AD. Several centuries later, during the Regency period of the early 19^{th} century, the Bath Hot Springs were particular popular amongst the aristocracy who travelled to Bath to "take the waters".

Interest in geothermal as an energy resource appeared more recently, when the oil crisis hit the UK in the mid-1970s, leading to a steep increase in the energy prices. This sparked new research into alternative energy resources, including geothermal (Downing and Gray, 1986). Studies of the geothermal potential of the rocks lying beneath the UK were undertaken (Downing and Gray, 1986; Lee et al., 1987), which continue to be used as a basis for geothermal exploration today (Busby, 2010) (*Figure 1*). Out of this initial surge of interest for geothermal energy, only one successful scheme emerged. The Southampton district heating scheme was installed in the 1980s and still runs today, using hot water (76°C) from a 1,800 metre deep borehole drilled into the Wessex Basin aquifer (Barker et al., 2000) (*Figure 1*). Initially, the scheme used only the geothermal water to provide heat but as the network underwent expansion, the geothermal resource was complemented by a gas-fired combined heat and power (CHP) plant, providing heat for 3,000 homes, 10 schools, and numerous commercial buildings (Lund and Boyd, 2015). Interest in geothermal waned in the 1990s with the drop in prices of fossil fuels as the UK focused its efforts on gas extraction from its North Sea reserves, a period known as the "Dash for Gas".

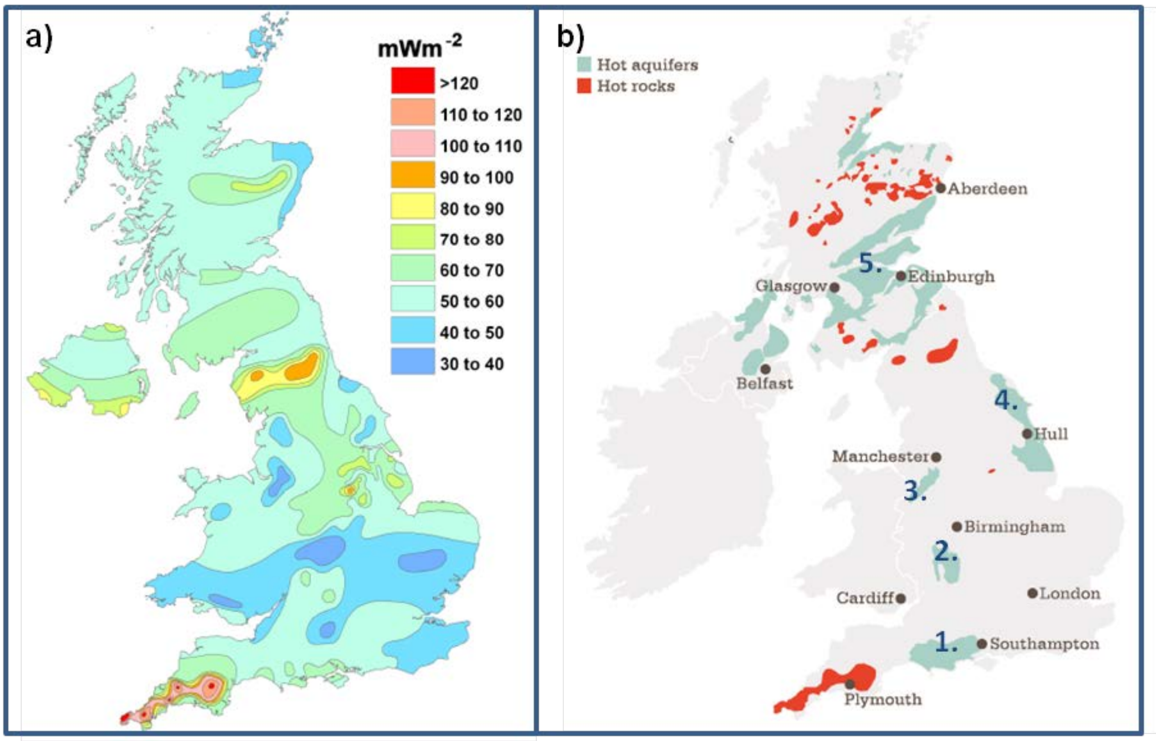

Figure 1. a) Heat flow map of the UK in milliWatt per meter square, with an average background heat flow of 52 mWm^{-2}. Note the high heat flow associated with the granites in Cornwall, Northern England and Scotland. Map from Busby 2010; **b)** indicative map of geothermal resources in the UK. The green overlay shows the Hot Sedimentary Aquifers: 1. Wessex Basin; 2. Worcester Basin; 3. Cheshire Basin; 4. East Yorkshire and Lincolnshire Basin; 5. Midland Valley Basin. The red overlay indicates the "hot rocks" of the UK, namely the granites mentioned in a). From IME, 2010.

During the past decade, the depletion of fossil fuel reserves, volatility of fossil fuel prices and concerns over green house gas (GHG) emissions have led to a resurgence in the interest in geothermal (Younger et al., 2012). The focus is now on developing local, renewable energy resources in order to minimise GHG emissions and provide energy security in the future. Geothermal energy certainly has a role to play in this new energy mix however geothermal development has not progressed as fast in this country as it has in neighbouring European countries, such as France or Germany (Curtis et al., 2016).

3.2. State of geothermal development in the UK

Due to its tectonic setting, away from plate boundaries and active volcanic centres, the UK has access principally to low enthalpy resources such as the hot sedimentary aquifers and medium enthalpy resources such as the granites (Figure 1). In the radiogenic granites at shallow depths in Cornwall, the heat flow is great enough to envisage power generation (Curtis et al., 2016) (Figure 1) but the main resources of the UK are the hot sedimentary aquifers, which offer opportunities for direct geothermal heat use. The inferred geothermal heat resource from UK sedimentary basins has been estimated at around 300 PetaJoules (PJ), which is around 100 times greater than the energy consumed every year for domestic and industrial heating in the UK (Busby, 2010; Younger et al., 2016). This is significant because decarbonising our heating will contribute significantly towards reducing our carbon emissions. Heating, which represents the single greatest end-use of our energy (Younger et al., 2012), accounts for 48% of our total energy consumption (IME, 2013) and around a third of our CO_2 emissions (PostNote, 2016).

Governmental support to the reduction of carbon emissions from the heating sector can be seen through the Renewable Heat Incentive (RHI), which aims to promote the development of low-carbon heating technologies (BEIS-RHI, 2016). It was reviewed in late 2016 and support for deep geothermal projects remains at a tariff of 5.14p/kWh of geothermal heat produced (BEIS-RHI, 2016). The government is also committed to developing infrastructure for district heating networks through the Heat Delivery Networks Unit (HDNU), which is providing support and funding to local authorities for building heating networks across the UK. Since its launch in 2013, the HDNU has provided grants for over 200 projects across 131 local authorities in England and Wales (BEIS-HDNU, 2017). Despite these schemes, the drive from government and local authorities towards developing geothermal is not great and is reflected by the lack of geothermal projects which have been successful so far.

In the following section, we describe the current geothermal projects underway in the UK, focussing first on the geothermal heat use (deep and shallow), then on deep geothermal power production and finally on new ideas about heat storage and heat scavenging.

3.2.1. Geothermal heat use

a. Deep geothermal heat use: Hot Sedimentary Aquifers and granites

The primary resource of geothermal heat in the UK are the low to medium enthalpy Hot Sedimentary Aquifers (HSAs), which are deep (>1,000 m) porous sedimentary rocks which contain water at high enough temperature to provide heating. The HSAs that lie at suitable depth for exploitation with current technologies are shown in Figure 1. A number of projects are underway in locations situated above these aquifers. For example Cheshire East Council are investigating a deep geothermal potential in Crewe and Wichavon District Council is looking into using deep geothermal heat for a new district heating scheme, using hot water from the Worcester Basin (Curtis et al., 2016). Investigative work at Science Central in Newcastle-upon-Tyne looking into the prospects of deep geothermal heat from the Fell Sandstone formation revealed a significant flow rate (88±1 mWm^{-2}, greater than UK average of ~50 mWm^{-2}). The borehole was not productive due to lower flow rates than expected however, and further research is being conducted in order to find a more optimal drilling spot (Younger et al., 2016).

Scotland is at the forefront of deep geothermal endeavours in the UK at the moment, with strong support from the Scottish Government through the Scottish Geothermal Challenge Fund (Low Carbon Infrastructure Transition Programme) and enterprising new geothermal companies like Town Rock Energy Ltd. In 2015, funding was awarded to the Guardbridge project in Fife, North Lanarkshire, which aims to tap into the HSA resources of the Midland Valley Basin to provide heating for the Guardbridge Energy centre, Guardbridge village and the neighbouring towns of Leuchars and Balmullo (Robinson et al., 2016). The geothermal well capacity is estimated at ~ 0.42 MW and would be used in parallel with a biomass plant (Robinson et al., 2016). Scotland is also looking at the resources available from its "hot rocks", the granites (Figure 1). A feasibility study of the geothermal prospects in the Hill of Banchory area has shown that heat from the underlying granite could complement the existing heat network and provide a competitive alternative against fossil fuel alternatives, providing considerable CO_2 savings (71,000 tons over 30 year period) (Hill of Banchory Geothermal Consortium, 2016).

b. Shallow geothermal heat use: Ground Source Heat Pumps

GSHPs are the most widely used geothermal technology in the UK and yet they represent only a tiny proportion of the heating sector. Indeed, the total heat pump sector (including both Air Source Heat Pumps (ASHPs) and GSHPs) only accounts for ~0.2% of the heating sector in the UK (Hannon, 2015). GSHPs constitute around a third of the total heat pump sector, facing competition from (ASHPs), which are easier to install as they do not require any foundation work, however they are season-dependent, whereas GSHPs are not. With only 17,760 GSHP installations by 2012, the UK lies far behind its European neighbours. In 2012, Germany had installed 264,800 GSHPs and France had installed 123,045 (Rees and Curtis, 2014). The comparison to other countries with similar climates suggests that there is considerable potential for further growth in GSHP installation in the UK over the coming decades (Rees and Curtis, 2014).

The main reason GSHPs have struggled to be developed in the UK is because the infrastructure is not in place to facilitate their implementation. GSHPs require foundation work to install the heat exchangers and if used for heating a number of buildings, a district heating network with pipes also needs to be installed. Only 1% of the UK's current heat demand is met by district heating networks, in contrast to 77% met by gas fired boilers. This lack of favourable infrastructure makes it difficult for GSHPs and district heating networks to be developed, hence the support from government through the Heat Delivery Networks Unit (HDNU).

The recent review of the RHI stresses the importance of heat pump technology for long-term emissions reduction and recognises the need to continue to develop the sector through to 2050 (BEIS-RHI, 2016). It offers a tariff of 8.95 p/kWh for GSHPs (BEIS-RHI, 2016). This stronger commitment from government to developing the GSHPs sector is likely to lead to an increase in installation and a development of the district heating networks.

3.2.2. Geothermal power production

a. Enhanced Geothermal Systems (EGS)

The rocks with the highest heat flow in the UK are the radiogenic granites in Cornwall (*Figure 1*) (Downing and Gray, 1986). Temperatures have been modelled to measure up to 200°C at 5 km depth (Beamish and Busby, 2016), making the Corubian granites the most propitious location for geothermal power production.

A research project undertaken at Rosemanowes in Cornwall during the 1980s and 1990s looked at Hot Dry Rock (HDR) technology, which consists in stimulating a geothermal reservoir by fracturing the granite to enhance fluid flow (Richards et al., 1994). Several EGS projects have been attempted in Cornwall since, such as the United Downs project and the Eden Project but no power plant has yet been built due to funding cutbacks (Atkins, 2013; Curtis et al., 2016). At the Eden Project developers are aiming to build a power plant with a capacity of 4 MWe. The power plant would produce electricity to supply the Eden centre and ~5,000 households, as well as heating for the tropical biomes of the Eden Project and potentially some district heating networks (Curtis et al., 2016).

If an EGS power plant in Cornwall were to be successful, this be would provide great momentum to the geothermal industry in the UK and in the world, as it would open the doors for geothermal power production in other granitic areas. If the projects continue to be unsuccessful however, the Cornwall deep geothermal project could be harmful to the nascent geothermal direct heat sector in the UK, confirming the decision-makers' and investors' fears that geothermal is too uncertain a technology to be relied upon.

b. Power from low and medium enthalpy resources

Power production can also be envisaged in low and medium enthalpy systems (water <180°C) using binary power plant technology, such as Organic Rankine Cycle (ORC) (see section 2.1). Binary geothermal power plants are less common but are starting to be used in geothermal settings such as Japan, Kenya and Turkey and as the technology matures, it may become more attractive in the UK. Moreover, this technology is already being developed in the UK for converting waste heat from industrial processes into power. If this technique proves successful, it could provide a gateway into geothermal power production in the near future. The use of binary cycle technolgy in geothermal would lead to a significant increase in geothermal resources available for power production in the UK, as waters with temperatures as low as ~70-80°C, such as those found in the deep geothermal HSAs, could be used to produce geothermal power.

c. Iceland interconnector

This section does not relate to geothermal production within the UK but it relates to geothermal energy use in the UK. In 2010, the Department for Energy and Climate Change led a review into the costs and benefits of developing a joint renewable energy project with Iceland, which would involve building a 500 MW geothermal plant in Iceland and a 1,200 km direct interconnector submarine cable to Northern Scotland. The analysis showed that the project could be competitive with other forms of renewables, such as offshore wind, but a number of factors could hamper the development, not least the negotiation of international treaties and building the longest submarine electric cable to date (IME, 2013). There have been no recent developments in this area, in particular since Brexit, but both the Icelandic and British governments remain open to the idea.

3.2.3. Heat storage and heat scavenging

Moving away from the more conventional geothermal technologies mentioned above, we now look at how we can use the subsurface for heat storage and how we can “scavenge” heat produced by human activity in the subsurface. Thinking innovatively about using the space around us to store and scavenge heat will enable us to reduce our carbon emissions further.

Heat storage in the Earth’s crust can take many forms and be implemented on many scales. Aquifer Thermal Energy Storage (ATES) is a technology that involves extracting cold water from an aquifer in the summer to provide cooling for the buildings and re-injecting the heated water, which is then extracted in the winter to provide heating. These schemes can be developed in cities where aquifers suitable for energy storage can be found below the surface, such as in London where the chalk aquifer could provide ATES in many locations (Shennan, 2010). Underground Thermal Energy Systems (UTES) could also be developed for the storage of waste heat from solar farms or industrial processes for example (Sanner et al., 2003).

The prime example of heat scavenging from our man-made environment is mine water heat extraction. Mine water is highly polluted so it cannot be used for any other purpose. Using this waste water as a heat exchanger is a great use of an otherwise useless fluid. Moreover, fluid circulation through mining systems is usually well documented so the drilling of the injection and extraction wells is better constrained than in conventional geothermal settings. Mine water heat extraction is currently being developed in Europe (Germany, Netherlands) and could have great potential in UK, especially with the extensive mine works in Northern England, Scotland and Wales. Several small local schemes already exist in Scotland (Shettleston and Lumphinnans) (Curtis et al., 2016). This technique could be developed to provide large scale district heating networks. For example, in Stoke on Trent, a district heating network that uses 43°C mine water as its heat source is being constructed (Curtis et al., 2016). Similar projects are under investigation in Glasgow (the ESIOS project) and in Wales (the SEREN project), where it is estimated that the disused mine water with an average temperature of 13.4°C could be used to heat ~20,000 homes.

Finally, other heat scavenging projects include the use of the waste water from the Roman Baths to heat the Abbey in Bath. A pilot project in the Borough of Islington in London extracts heat from the Underground to provide heating for three estates and two leisure centres, and if successful this type of scheme could be implemented throughout much of London. In Stockholm in Sweden, heat is extracted from the treated waste water from the underground sewage system and provides energy for the district heating network. Such a scheme could be envisaged in similar cities in the UK. These examples demonstrate that there are many innovative solutions that involve using the heat produced by human activity in the surface to reduce our carbon emissions.

4. Future perspectives for geothermal in the UK

4.1. Current barriers to geothermal development

We have touched upon the geological and geographical challenges faced by geothermal technologies. These are not the only factors preventing the development of geothermal energy in the UK, however. Geothermal energy development also faces a number of economical, technical and political obstacles.

The main economic barriers to geothermal development are the high initial capital costs and high risks associated with resource exploration and development (IEA, 2010). The uncertainty attached to geothermal exploration is often a deterrent to investors. Another economic barrier, which is also a political one, is the uncertainty around the future of existing incentive schemes such as the Renewable Heat Incentive. The RHI has recently been reviewed, ensuring continued support to low-carbon heating technologies (BEIS-RHI, 2016). However, the history of solar PV development in this country is a testimony to the damage that rapidly changing governmental policies can cause to emerging low carbon technologies. The solar energy industry, which was flourishing in the UK up until 2015, encountered serious difficulties when the government announced a sudden 65% cut to the feed-in tariff (STA, 2015). The lack of strong governmental commitment to low carbon technologies development is one of the main obstacles to geothermal development in the UK.

The technical challenges faced by geothermal in the UK are due to the fact that that the majority of geothermal technologies being investigated are relatively immature, in particular Enhanced Geothermal Systems (EGS), binary power plants and district heating from Hot Sedimentary Aquifers (HSAs). These new technologies have technical uncertainties associated with them, related to the drilling of wells to significant depths, the stimulation of productivity and accessibility of the reservoir and the control and mitigation of potential induced seismicity (IEA, 2010). These obstacles are enhanced by the shortage of geothermal scientists and engineers in the UK who can provide the expertise required for the development of these projects. Furthermore, there is no risk insurance framework in place in the UK that provides a financial cover in the early and risky stages of geothermal exploration. Such schemes are common in other European countries like France, Germany, Iceland, Netherlands, Switzerland (Jaudin, 2013*)*. Such a framework is necessary for geothermal because of its limited market size so as to allow the technology to progress along its learning curve, in particular for EGS.

Several other barriers emerge from the immaturity of geothermal technologies, such as the low levels of awareness of the decision makers and general public about the various options offered by geothermal technologies and the opportunities they present for reducing its carbon emissions, particularly in the heating sector (Curtis et al., 2016). The limited understanding about these technologies is reflected by the public concern over potential environmental issues such as seismicity, subsidence and pollution, which are often disproportionate to the actual associated risk (IEA, 2010). The low level of interest in geothermal development means that the legal framework relating to the licensing of the resource and to the regulation of the production and distribution, is not in place to enable the smooth development of such resources (GTR-H, 2009).

4.2. Evolution of these barriers

As fossil fuels become scarcer and more expensive, low carbon alternatives will become more competitive. The main drivers for change in geothermal development in the UK are likely to come from reliable political commitment towards incentivising low carbon technologies and from the funding of research into the implementation of geothermal technologies in the UK-specific context (GTR-H, 2009; Curtis et al., 2016). Reducing the uncertainties around new geothermal technologies through more research and the implementation of demonstrator projects will provide better constraints on the UK's geothermal resources and improve our knowledge of drilling and reservoir management. Successful demonstrator projects will also lead to an increase in awareness and understanding of geothermal opportunities amongst the public. In order for these projects to be developed, a risk insurance framework is necessary, as it will allow the geothermal industry in the UK to overcome initial financial and technical barriers. A European geothermal risk insurance fund is being developed by the European Union (Fraser et al. 2013), which might help geothermal development in the UK, however the extent to which the UK will be able to benefit from this fund will depend on the outcome of Brexit negotiations.

In economic terms, worldwide research into geothermal technologies will lead to a decrease in the costs associated with geothermal development, principally through the development of more appropriate drilling technologies, more strategic drilling campaigns and a better understanding of reservoir stimulation and management. The use of direct geothermal heat in the UK, for example from its HSA resources, should become more attractive as the UK continues to develop its district heating networks (BEIS-HDNU, 2017) and suitable infrastructure becomes available. District heating network infrastructure can be expensive and careful modelling of the trade-off between the parameters involved (temperature of reservoir, temperature demand, length of pipe network, size of pipes, power of heat pump…) needs to be considered in order to achieve the most optimal use of geothermal resources. Once a district heating network is in place, the network can be incrementally increased as demand increases by drilling additional boreholes into the reservoir.

4.3. Future Energy Scenarios

We use the National Grid's Future Energy Scenarios (FES, 2016) as a reference framework to investigate how geothermal technologies might fit into the energy mix over the next 30 years and beyond. The four scenarios look at different ways in which our energy production, efficiency and demand are likely to change within the next few decades and how this will affect our chances of reaching our 2020 and 2050 renewable energy targets. The 2020 target aims for the UK to provide 15% of its energy needs from renewable sources and is a stepping stone towards the legally binding 2050 target of reducing UK carbon emissions by at least 80% of 1990 levels (CCC, 2015). The EU 2020 target is missed in all scenarios, including in the "Gone Green" scenario, which considers an economy focused on environmental goals (FES, 2016). This is a sobering indication that we are sorely behind our commitments, in particular in the heating and transport sectors. The FES report states that in order to meet our 2020 target, a 60 TWh (170%) increase in renewable heat and a 25 TWh increase in renewable transport are required. In light of this, geothermal resources offer a great opportunity for decarbonising our heating sector.

The Future Energy Scenarios are summarised in the table below and we give an indication of the role geothermal might have to play in each scenario.

Table 2 - A summary of the National Grid's Future Energy Scenarios towards 2050 and the role of geothermal within each scenario

National Grid's 2016 Future Energy Scenarios	Role of geothermal
Gone Green Focus on long-term environmental goals to ensure that 2050 carbon reduction target is met. Policy interventions are both ambitious and effective in reducing green house gas emissions.	A strong commitment to environmental goals on a national and European level ensures the continued and reliable support for emerging low-carbon technologies like geothermal. The strong emphasis on renewable and low carbon electricity generation could lead to increased interest in EGS and binary power plants. District heating networks flourish, with the potential for developing district heating from HSAs and mine water extraction.
Slow Progression Some progress towards decarbonisation but at a slower pace than society would like, due to economic conditions that limit society's ability to transition as quickly as desired to a renewable, low carbon world.	Despite difficult economic conditions, district heating features strongly as a relatively cost effective solution to battle against fuel poverty. In favourable locations, geothermal district heating could be developed.
No Progression Business as usual prevails, with a focus on the short term, concentrating on affordability above green ambition.	Very little scope for geothermal development in the face of the prevalence of gas and low electricity demands do not incentivise the development of new technologies like EGS.
Consumer Power Market-driven world, with limited government intervention. New technologies are prevalent and focus of the desires of consumers over and above reducing GHG emissions	Focus on gas, in particular the exploitation of UK shale gas, so there is little scope for geothermal direct use for heating. There is some small-scale, low carbon electricity generation. Innovation leads to high levels of local energy production and storage, in particular from solar energy.

The likelihood for geothermal development in the UK over the next 30 years is strongest if there is a real commitment from government to drive policy towards achieving environmental goals and developing low carbon technologies. District heating offers an attractive and cost-effective option in a scenario of harsh economic conditions, which the UK is likely to experience in the aftermath of Brexit. In this case, geothermal direct use from HSAs and mine water extraction could become attractive in the right locations, i.e. where the heat demand is great enough to justify drilling into a geothermal reservoir and building a district heating network. As expected, there is little scope for geothermal development in the "business as usual" scenario as the focus remains of conventional energy production, in particular with the use of individual gas boilers for heating.

In light of recent political events and our departure from the European Union, there is not guarantee the government will stick to its 2020 targets. It is not impossible to envisage a situation similar to the “No Progression” or “Consumer Power”, in which the UK will strive to develop its industry and economy at all costs in order to try and remain competitive on the global market. In this context, geothermal technologies would struggle to be attractive, in particular in the heating sector where gas will continue to prevail.

However sooner or later, the UK government will have to commit to low carbon and renewable technologies as it is legally bound to its 2050 renewable energy targets (CCC, 2015). With this target in mind, and as geothermal technologies develop and become more mainstream on the global stage, geothermal could well play a role in the energy mix and the decarbonisation of our heat and electricity generation. A sensitivity analysis in the FES report shows that the heating sector could be decarbonised faster than present estimates suggest if we adopt mass electrification of our heating, with the development of heating networks, heat pumps and heat storage. Our paper has shown that geothermal offers numerous and varied opportunities in this field and as such can provide a significant contribution towards accelerating the decarbonisation of our heating and towards our 2050 target.

5. Policy recommendations

Geothermal has a real role to play in the diversification and decarbonisation of the UK’s energy mix. The UK is far behind many of its European neighbours however when it comes to the use of its greatest geothermal asset, geothermal heat, either through direct use in district heating networks or with Ground Source Heat Pumps. In order to accelerate the development in this country of geothermal heat, and more broadly geothermal energy use, here are the recommendations put forward by the authors.

In order to increase the support for geothermal, it is necessary to inform decision-makers, investors and the general public of the opportunities offered by geothermal energy in the UK, in particular for low carbon, local and reliable heating. In order to do this, we need effective communication campaigns to bridge the gap between the scientific and engineering communities and the public. Greater awareness of the number of opportunities offered by geothermal can open the door to innovation within the energy sector and an accelerated departure from the use of conventional, carbon intensive alternatives. If we do not develop the awareness of geothermal, we run the risk of investing further in unsustainable resources and missing out on a valuable opportunity which would enable the UK be at the forefront of technological and energy innovation.

Furthermore, in order to develop awareness and understanding of geothermal opportunities in the UK, data about heat capacities and heat flow rates at depths must be collected and made widely available. This could be achieved by collaboration between the British Geological Survey with its knowledge of the subsurface geology and structures, the Environmental Agency with its database of boreholes and flow rates as well as the hydrocarbon industry with its knowledge of rock properties and fluid flow in the subsurface. The UK deep geological data needs to be made more easily accessible to non-specialists by providing interactive maps, similar to the map already available for

Combined Heat and Power projects in the UK[1] or the GeoDH map, which displays district heating opportunities from geothermal in Europe[2]. Such interactive and accessible resources will help to educate the public on geothermal opportunities and will facilitate the training of technicians and decision-makers for the development and support of geothermal projects.

As geothermal opportunities become more popular, legal and financial frameworks need to be in place to favour their development. Firstly, a legal framework must be specified, which will facilitate the implementation of geothermal projects and address their specific requirements, such as the clear definition of the ownership of geothermal resources (GRT-H, 2009). These frameworks already exist for oil and gas, mineral and water resources, and a new framework needs to address the specific requirements of the geothermal industry. This will simplify procedures for the permitting of projects and enable them to progress beyond the feasibility stage. Secondly, innovative financial models are required to make geothermal technologies more competitive and more attractive to investors. In order for geothermal opportunities to develop, policies are required that cover the financial risk associated with geothermal exploration and drilling (GRT-H, 2009; EGEC, 2014). In addition, geothermal will only ever be truly competitive (as will other renewables, for that matter) when a level playing field is established, whereby green house gas emissions are taxed and fossil fuels are no longer given the advantage, in particular in the heating sector (EGEC, 2014). In terms of competition against other renewables, geothermal energy presents an undeniable advantage as it can provide continuous base load power and as such is competitive against other renewable technologies, such as solar. Moreover geothermal thermal storage offers possibilities that can complement, rather than compete against solar, as excess solar thermal energy can be stored in Underground Thermal Energy Systems (UTES). Geothermal energy is complementary to the renewable energy mix.

6. Conclusions

The aim of this paper is to clarify some of the confusion that exists around geothermal energy, in particular regarding geothermal resources in the UK. We have given a description of the resources available in this country, summarizing the projects that are currently being developed and presenting ideas about new geothermal applications that could be developed in the near future. These ideas show that geothermal has a very real role to play in the renewable energy mix. The economic, political and technical barriers that are restraining geothermal development in the UK are identified and we investigate how these are likely to change over the next 30 years. Finally, recommendations are given that provide an insight into how to accelerate the development of our geothermal resources. We need to improve our understanding of our geothermal resources through more research and advertise their potential through improved communication between the scientific, engineering and public sectors. We emphasize the need for reliable, continued support from government towards emerging geothermal technologies in order to foster their development.

[1] http://chptools.decc.gov.uk/developmentmap/. Accessed 03/03/2017.
[2] https://map.mfgi.hu/geo_DH/. Accessed 03/03/2017.

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