A Review of Deep Geothermal Energy and Future Opportunities in the UK

Sean M. Watson[1], Rob Westaway[1] and Gioia Falcone[1]

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

s.watson.3@research.gla.ac.uk

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ABSTRACT

The UK's geothermal heat resource is significant with areas of potential geothermal resource matching areas of high heat demand in many areas of the UK. It would be technically feasible, therefore, to utilise low enthalpy geothermal heat for space heating through the use of district heating systems. The consequences of developing a substantial part of the UK's geothermal resource are considerable. The opportunity to supply baseload heating from low enthalpy geothermal energy would dramatically reduce the UK's emissions of greenhouses gases, reduce the need for separate energy storage required by intermittent renewable technologies such as wind and solar, and lessen the dependence on imported oil and gas, contributing to increasing the UK's energy security for the foreseeable future. One potential catalyst for developing low enthalpy geothermal energy in the UK is the opportunity to repurpose abandoned hydrocarbon wells, for geothermal heat production and seasonal heat storage. DGSW technologies may have a role to play in fulfilling this opportunity. The idea of Deep Geothermal Single Well (DGSW) heat production has existed for many years. However, there are relatively few studies of its technical and economic feasibility available in the public domain and only one field trial has been carried out so far, in an existing well. This has created uncertainty, with advocates of the technology suggesting thermal outputs that appear exaggerated, and detractors claiming that the concept can never be economic unless the capital cost of drilling has already been reduced. However, because this technology offers the potential of delivering geothermal heat projects with a minimum of site-dependent research, the possibility exists of achieving cost-effective solutions.

1. INTRODUCTION

The catalyst for geothermal exploration worldwide is the need to produce low carbon renewable energy (Younger 2015). An assessment of the potential geothermal resource in Britain was undertaken in the 1970's as a consequence of the global oil crisis. However, this assessment was based upon identifying resources capable of generating electricity.

Renewed interest in the geothermal potential of the UK has recently emerged and can be attributed to two developments: (1) a focus on renewable heat, instead of electricity, generation and resulting re-assessment of the lower temperature resource; and (2) a rigorous re-assessment of UK heat flow data to account for the effects of palaeoclimate and topography. Efforts to address the latter have suggested that the UK's potential geothermal resource have been underestimated and that higher temperatures may be found at shallower depths than previously believed (Westaway and Younger 2013, 2016; Busby et al 2015; Busby and Terrington, 2017).

The use of geothermal energy, whether directly for heat and cooling, or for power generation is a well-established and stable technology. When considered in the context of the "energy trilemma" (sustainability, equity and security), geothermal energy is able to address each of these issues. Geothermal energy technologies are low carbon, clean, green, sustainable and do not suffer from the intermittency problems experienced by other renewable energy sources such as wind and solar (Younger et al., 2012; Younger., 2015).

In the UK, heat represents ~50% of total energy demand. With summer 2018 being the joint hottest on record in the UK, geothermal cooling systems may also soon be in high demand. Around 40% of energy is used on an annual basis for space heating (DTI, 2002). The heating demand dominates the use of gas in the UK. 50% of the total gas consumption is for domestic heating and cooking and a further 25% is used by industry (DUKES, 2018). Agriculture is another heavy energy consumer and greenhouse gas emitter and is exposed to fluctuating energy prices; geothermal heating/cooling can thus play a key role in decarbonising this sector.

The UK Climate Change Act (2008) delivered a binding commitment to reduce emissions of greenhouse gases by 80% by 2050. Offshore wind and photovoltaic electricity production continue to deliver success stories. However, The UK Committee on Climate Change (Bell et al 2016) stated that only decarbonisation of heating in the UK could deliver the major reduction in emissions needed to meet the 2050 target.

Low enthalpy geothermal energy is ideal for space heating and hot water requirements, greenhouses and aqua-culture amongst other applications. This presents an opportunity for the development of geothermal energy in the UK.

2. UK ONSHORE GEOLOGY AND EXISTING DATA

The surface geology of the UK is extremely well known due to extensive mapping by the British Geological Survey and others. However, we know much less about the deep geology of the UK onshore in comparison to offshore areas of the North Sea and Atlantic Margin where extensive petroleum exploration has taken place (Gluyas et al 2018a).

There are a number of deep onshore sedimentary basins in the UK in which the thickness of sedimentary (and thus, likely, porous and permeable) water bearing, rock exceeds 2km (Gluyas et al 2018a). The age of these basins is typically older (upper Palaeozoic) in northern England and Scotland and younger (Mesozoic) in the south of England. Although the sedimentary basins will contain porous sedimentary rocks there is an uncertainty of the connectivity of pore spaces allowing the transport of fluid through these potential aquifers; there is thus greater uncertainty regarding permeability than porosity. This remains a challenge for quantifying the geothermal resource in the UK prior to drilling of geothermal wells. In addition to the sedimentary basins, the UK also hosts suites of radiothermal granite batholiths, which are also a target for geothermal energy projects. For example, the Rosmanowes project of the 1980's and the current United Downs project are drilled into Variscan (Permian granites) of south west England.

A knowledge of the regional heat flow pattern in the UK is fundamental to any assessment of geothermal potential. Much of the UK onshore is covered by 2D seismic data but such data does not contain information on temperature or heat flow. Temperature can be measured in mines and boreholes as can heat flow. Heat flow can also be measured at surface although such measurements may not be fully representative of heat flow at depth due to palaeoclimatic effects resulting from chilling of the subsurface during the last Ice Age (Westaway and Younger 2013).

The UK has more than 2000 onshore petroleum exploration wells (compared with about 9000 offshore wells) drilled since the beginning of the twentieth century (Davies et al 2013). There are currently 230 onshore Petroleum Exploration and Development Licenses that include 120 sites with 250 operating wells. Most of these were drilled in the petroleum provinces of the East Midlands, Wessex, Hampshire and the Weald, with fewer drilled in the Midland Valley of Scotland and the Cheshire Basin. Onshore commercial drilling activity since the 1980's has resulted in additional subsurface temperature measurements being added to the UK's dataset of temperature and heat flow measurements (Burley et al 1984). Most of the onshore wells terminate at depths between 1km and 2km; a few penetrate to depths greater than 2km. This contrasts with the situation offshore in which most wells have been drilled to depths of around 3km and many in excess of 5km.

3. SUMMARY OF GEOTHERMAL ENERGY IN THE UK

3.1 Geothermal exploration in the 19th and 20th Centuries

In the UK, the visible manifestation of geothermal activity can be seen at thermal springs, the best-known being at Bath, Bristol, Buxton and Matlock (Downing and Gray 1986). These waters are meteoric in origin but have been heated by circulation to depths of maybe 1-2km (Downing and Gray 1986).

In the latter half of the 19th century, the British Association for the Advancement of Science investigated the thermal state of the subsurface. Numerous measurements of temperature were made in boreholes, particularly those associated with the developing ironstone and coal mining industries, for example in the Midland Valley of Scotland. Most notably, Sir William Thomson, Lord Kelvin, conducted observations of temperature and thermal resistance in the Blythswood and South Balgray boreholes in what is now suburban Glasgow (Thomson et al 1868; 1869).

As Gluyas et al (2018a) have summarised, in 1961 it was demonstrated that the hot, radiothermal Weardale Granite exists at depth beneath County Durham when the Department of Geology at Durham University drilled the Rookhope borehole in Weardale. This well proved the eroded top surface of Caledonian (Devonian) granite at a depth of 385 m in a region where there is no outcrop of granite.

The search for geothermal energy in the UK began in the 1970's in response to the global oil crisis and at a time when the petroleum resource offshore of the UK lay largely undiscovered. Seven deep geothermal exploration boreholes were drilled on the basis of preliminary studies conducted in the 1970's, although these were not completed until 1980-1985 by which time the UK had become a petroleum exporter (Gluyas et al 2018a). Three of the wells were drilled and tested at Marchwood and Southampton in southern England, and Larne in Northern Ireland, to investigate the geothermal potential of the Permo-Triassic sandstones in different sedimentary basins. This programme was continued in 1984 with the drilling of the Cleethorpes-1 well to a depth of 2100 m. The principal objective was to investigate the nature, water yielding potential and temperature of the Basal Permian Sands and Breccia, with the Triassic Sherwood Sandstone Group as a secondary target (Downing and Gray 1986). Three wells were targeted at radiothermal Variscan granite; while these wells, drilled at Rosemanowes in Cornwall (SW England) as part of the "Hot Dry Rock" Programme, received much attention, none made it to production (Richards et al 1991). The borehole that can be considered successful, in that it led to an operational geothermal heat project, was that drilled at Southampton. Since 1987 this borehole has supplied water at 75°C with thermal power of 1.7 MW_T; it forms the basis for the Southampton District Energy scheme, delivering heat and power to a hospital, university and commercial businesses in central Southampton.

3.2 Renaissance of geothermal exploration

The failure of the Rosemanowes project resulted in a hiatus in exploration for geothermal energy for the next twenty years. The renaissance began, again in Weardale, County Durham, where in 2004 a well was drilled at Eastgate to a depth of 998 m. The background to this project is summarised by Gluyas et al (2018a) and explained in detail by Manning et al (2007). This well encountered naturally fractured Weardale Granite as planned. The bottom hole temperature was 46°C, indicating a heat flow of 115 mW/m^2. This well produced saline water at a temperature of 27°C from a fractured zone at 411 m depth. This Eastgate-1 borehole proved capable of producing water at a rate of 140 m^3/h (39 l/s) per metre of drawdown. An appraisal well, Eastgate-2, was drilled in 2010 around 700 m from Eastgate-1 to determine whether the fractures were pervasive throughout the granite or were limited to the vicinity of a major fracture in the granite, known as the Slitt Vein. The granite at Eastgate-2 proved the same geothermal gradient as at Eastgate-1, but also proved to be impermeable, confirming that the fracture permeability at Eastgate-1 is associated with the Slitt Vein.

A further geothermal exploration well was subsequently drilled in the city centre of Newcastle upon Tyne, named the Newcastle Science Central well. This reached a depth of 1.8 km and targeted the Lower Carboniferous Fell Sandstone Formation in an area near the Ninety Fathom Fault, a major normal fault of Carboniferous age. This well confirmed the high regional geothermal gradient but demonstrated that the Fell Sandstone in this locality is extremely ‘tight’, no useful rate of water production being feasible (Younger et al 2016).

The potential geothermal resource in Cornwall has not been investigated since the 1980’s. However, at the time of writing, a project is currently under way to drill two deep geothermal wells at the United Downs site near Redruth, also near the original Rosemanowes boreholes. These wells will reach depths of 2.5 km and 4.5 km. The design concept envisages injected water descending through the local fracture network and becoming heated, the deeper well being expected to produce water at 190°C, which will be used to generate 1 MW of electrical power. (United Downs, 2019). Furthermore, work has been completed to provide a 400 m deep geothermal well at the Jubilee Swimming Pool in Penzance, also in Cornwall (Jubilee Pool, 2019). This well is expected to heat a section of the swimming pool to 35°C.

In recent years significant research has been conducted on behalf of the Scottish Government to investigate the potential geothermal resource in Scotland (Gillespie et al 2013; Scottish Government 2015). Most recently, in the Clyde Gateway Regeneration area of the east end of Glasgow, drilling of observational and monitoring boreholes has commenced at the Glasgow Geothermal Energy Research Field Site (GGERFS). This site is part of the Natural Environment Research Council (NERC) funded UK Geo-energy Observatory (UKGEOS) project. The objective of the GGERFS is to investigate the geothermal potential of the flooded, abandoned mine workings beneath this area of the city (Monaghan et al 2017). Flooded, abandoned mine workings indeed present the “low hanging fruit” of the potential geothermal resource in the UK. Adams and Gluyas (2017) found that across the UK, a conservative estimate of the resource in flooded mine workings is around 38,500 TJ of heat, enough to heat around 650,000 homes. Projects of this type in the UK will benefit from expertise obtained from existing projects in other countries, such as Germany (e.g., Ramos and Falcone, 2013).

Downing and Gray (1986) provided the first comprehensive nationwide assessment of geothermal potential for production of hot water from Permian and younger strata. Their work has formed the basis for the more recent reviews by SKM (2012) and Atkins (2013). Busby (2014) provided a summary of the geothermal heat resource potential for the UK, indicating a minimum potential of 200 EJ. Such a resource, if exploited, could supply the current annual UK heating requirements for about 100 years.

4. FUTURE OPPORTUNITIES

4.1 Repurposing hydrocarbon wells

Despite the potential of geothermal energy, the high technical and economic risk at the exploration stage currently acts as a significant disincentive to development. One way to reduce this risk is to target well-characterised hydrocarbon reservoirs; this can also substantially reduce drilling costs.

The geothermal potential of hydrocarbon wells has been investigated by several authors, with pilot projects already implemented worldwide and pre-feasibility studies carried out (e.g., Liu et al, 2018; Singh et al, 2017; Al-Mahrouqi and Falcone, 2016; Alimonti et al, 2014; Auld et al, 2014; Westaway, 2016; Gluyas et al 2018b). Although offshore hydrocarbon fields offer significant geothermal energy potential (e.g., Gluyas et al, 2018b; Lefort, 2016; Auld et al, 2014) it is likely that only electricity generation would be appealing in such remote environments and exclusively for in-project utilisation, unless interconnecting export grids become available (e.g. from Iceland). As previously stated, around 2000 wells have been drilled onshore in the UK. There are currently 230 onshore Petroleum Exploration and Development Licenses with 120 sites and 250 operating wells, producing 20000-25000 boed. The UK regulatory framework does not permit retrospective repurposing of hydrocarbon wells for geothermal use; once hydrocarbon production ceases, wells must be plugged and abandoned by the operator. If regulations are changed in the future, there is the potential for reusing existing energy infrastructure to provide sustainable, low-cost heat from these hydrocarbon wells.

4.2 Deep Geothermal Single Wells

One technological option which could be applied in the context of repurposing hydrocarbon is deep geothermal single well (DGSW) heat production. The term DGSW denotes any geothermal project design that utilizes a single borehole (rather than a doublet), and which extends into the 'deep geothermal' regime, which under current UK regulations means depth >500 m; many possible variants exist, including both open- and closed-loop designs. The idea of DGSW heat production has existed for many years, but with no consensus regarding its potential applicability: proponents have made claims regarding thermal outputs that appear exaggerated, whereas detractors have stated that the concept can never be economic unless the capital cost of drilling has already been discounted. However, because this technology offers the potential of delivering geothermal heat projects 'off the shelf' with a minimum of site-dependent research, the possibility exists of achieving cost-effective solutions. Westaway (2018) investigated this topic subject to environmental and subsidy regimes applicable in the UK. Under these conditions, the variant of the technology with greatest potential for cost-effectiveness is the hcDGSW, or conductive DGSW with heat production via heat pump. Analytical modelling enables the physics of the heat-exchange processes within a hcDGSW to be approximated. It is thus established that this option can indeed be cost-effective under the current UK subsidy regime for deep geothermal heat, provided boreholes are deep enough and in localities where the geothermal gradient is high enough. The environmentally optimum operational mode (optimizing savings in CO2e emissions) involves heat production at a lower rate than the economically optimum mode (maximizing profit). If such projects are subsidized from public funds, a particular operational mode might be specified, maybe as a compromise between these optima. After the 20-year duration of the subsidy, the technology might well no longer be economic, but the infrastructure might be easily repurposed for seasonal heat storage, thus offering the potential of making a significant long-term contribution to sustainable future heat supply. These preliminary results indicate that more detailed appraisal of this technology variant is warranted.

4.3 CESI Project and Future Work

A research project funded by the EPSRC National Centre for Energy Systems Integration (CESI) and supported by industrial partners is currently underway to investigate the most favourable candidate sites for geothermal repurposing of onshore hydrocarbon wells in the UK. The aim is to present P10-P50-P90 ranges of recoverable heat resources for selected case studies, following established practices in the petroleum sector. The study encompasses infrastructure longevity issues of ageing/abandoned fields. It also challenges the current UK regulatory framework, which – as already noted - does not permit retrospective repurposing of hydrocarbon wells for geothermal use. Socio-environmental issues are also covered, considering that several projects have been delayed or cancelled because they failed to meet social or environmental expectations, although they met technical and economic requirements.

Table 1: Summary of deep boreholes drilled in the UK for geothermal exploration purposes

Location	**Completion**	**Well depth (m)**	**Bottom hole temperature (°C)**	**Main aquifer depth (m)**	**Aquifer temperature (°C)**
Rosemanowes RH11	December 1981	2175	90	2100	55-70
Rosemanowes RH12	October, 1981	2143	90	Not identified	N/A
Rosemanowes RH15	January 1985	2652	100	Not identified	N/A
Marchwood	February 1980	2609	88	1672-1686	74
Larne	July 1981	2873	91	960-1247	40
Southampton	November 1981	1823	77	1725-1749	76
Cleethorpes	June 1984	2092	69	1093-1490	44-55
Eastgate-1	December 2004	995	46	411	27
Eastgate-2	July 2010	420	-	Not present	No flow
Science Central	July 2011	1821	73	1418.5-1795	No flow
United Downs	Drilling	2500/4500	190 (est.)	4500	190 (est.)
Jubilee Pool, Cornwall	2018	400	35	400	35

Modified from Younger et al (2012, 2016), and Gluyas et al (2018a).

5. CONCLUSIONS

The UK's geothermal heat resource is significant with areas of potential geothermal resource matching areas of high heat demand in many areas of the UK. It would be technically feasible, therefore, to utilise low enthalpy geothermal heat for space heating through the use of district heating systems. The consequences of developing a substantial part of the UK's geothermal resource are considerable. The opportunity to supply baseload heating from low enthalpy geothermal energy would dramatically reduce the UK's emissions of greenhouses gases, reduce the need for separate energy storage required by intermittent renewable technologies such as wind and solar, and lessen the dependence on imported oil and gas, contributing to increasing the UK's energy security for the foreseeable future. One potential catalyst for developing low enthalpy geothermal energy in the UK is by repurposing abandoned hydrocarbon exploration wells, for geothermal heat production and seasonal heat storage. DGSW technologies may have a role to play in fulfilling this opportunity.

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