Feature

Unlocking deep geothermal energy in the UK using borehole heat exchangers

In the wake of COP 26, the international community is aiming to reduce carbon emissions by adopting alternative and renewable energy sources. Deep geothermal energy can help to achieve this as it represents a low carbon-emitting energy resource that can provide a constant base load of energy. In the United Kingdom, the development of deep geothermal has been limited due to high geological uncertainty and risk. Past exploration has focused on hot sedimentary aquifers and hot dry-rock granites, with limited success. To mitigate risk and extract heat with a lower reliance on geological properties, such as permeability, new development methods have been conceived using deep borehole heat exchangers, where fluid is circulated in a closed-loop system. Feasibility studies have been undertaken through modelling of deep borehole heat exchangers with the hope that these novel technologies can be used to exploit geothermal energy.

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In November 2021, delegates from COP 26 initiated discussions on the delivery of the 2015 Paris agreement, and re-iterated the need to limit global warming by 1.5°C and reach net-zero emissions by 2050. To achieve this, alternative energy sources to traditional fossil fuels are required. Geothermal energy can help meet the demand left behind by oil, gas and coal by tapping into thermal stores within the Earth's crust, producing a weather-independent, constant base load of energy. In the United Kingdom, geothermal energy is exploited from both shallow and deep sources. Typically, shallow geothermal developments use borehole heat exchangers to extract energy within the upper 300 m of the crust, where the Earth's surface is heated by the sun. Conversely, deep geothermal developments extract geological fluid heated by the Earth's natural thermal gradient (Fig. 1). Shallow systems in the United Kingdom can operate with low-risk by using a 'closed-loop' system with fluid circulated in a U-tube underground. As of 2021, government grants are available for such systems with new subsidies announced for heat pumps, with the aim to reduce carbon emissions produced from gas boilers.

Deep geothermal resources are broadly split into two categories: conventional and unconventional. Conventional resources are rocks in the subsurface which have sufficient fluid, heat and permeability to allow energy extraction. Past exploration activity in the United Kingdom has explored conventional resources, targeting hot sedimentary aquifers (HSAs), such as sandstones within the Permo-Triassic basins of central and southern England. Unconventional resources are where fluid or permeability is lacking. For example,

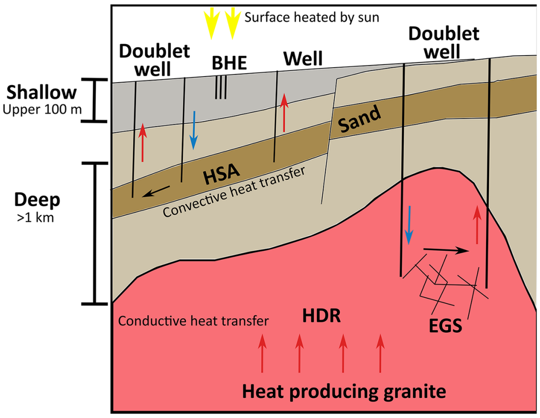

Fig. 1. A schematic diagram demonstrating different extraction methods for deep geothermal energy. BHE, borehole heat exchanger; EGS, enhanced geothermal system; HSA, hot sedimentary aquifer.

hot dry-rocks (HDRs) have been explored in Cornwall as enhanced geothermal systems (EGSs). EGSs create artificial fractures to enhance permeability such that fluid can be circulated through the reservoir between two or more wells. In a doublet EGS (two well system), cold fluid is injected, warmed by the rock in the artificial fractures and then extracted through a second producing well.

Until recently, an 'open-loop' system, where geological fluid is circulated in the reservoir of a HSA or HDR, usually via a doublet system, has been considered the primary method of energy extraction. In such systems, geological risk is high as there is a reliance on geological properties, such as permeability, heat stores and the presence of fluid. The consequence of this risk has been minimal investment and development of deep geothermal resources in the United Kingdom. However, new technological developments that mitigate these risks through a lower-cost, 'closed-loop', single well system have resulted in a renewed focus on deep geothermal resources.

Geothermal exploration and development in the United Kingdom

Exploration for deep geothermal energy in the United Kingdom began when the 1973 oil embargo triggered national research into alternative energy sources. Exploration targeted areas of high to moderate heat flow, focusing on low-temperature (<100°C) HSAs and high-temperature (>150°C) HDRs nationwide. HSAs were explored in Permo-Triassic basins including the Cheshire, Worcester, East England, Wessex Basins and undivided basins in Northern Ireland, with the total resource estimated to be 327×10^{18} J. The granitic HDRs that were explored include the Cornubian, Lake District and Eastern Highlands Batholiths. The drive for geothermal is well documented at this time with a comprehensive review by Downing and Gray in 1986. However, research stalled after the embargo was lifted, coinciding with significant North Sea oil discoveries. By the 1980s, the United Kingdom briefly became a net exporter of petroleum. Prior to 1984, seven deep geothermal exploration wells had been drilled in the United Kingdom, with four targeting HSAs and three HDRs. Only one well (in Southampton) was developed for production from the HSA targets. The HDR wells were part of the Rosemanowes field trial that successfully investigated the concept of hydraulic fracturing. However, these wells failed to yield temperatures high enough for electricity generation and development.

In recent years, the drive for a carbon-free economy has renewed the focus on deep geothermal energy. Three boreholes were drilled between 2004 and 2011 exploring high heat flows associated to the North Pennine Batholith (>90 mW m^{-2}). The Eastgate-1 borehole (2004) targeted water filled natural fractures in granite to a depth of 995 m (Fig. 2(a)), the Eastgate-2 borehole (2010) investigated the lateral continuity of the fractures and the Newcastle Science Central Deep Geothermal borehole (2011) tested the geothermal potential of the Fell Sandstone Formation.

The Eastgate-1 borehole intercepted natural fractures with a high permeability zone at 410–413 m

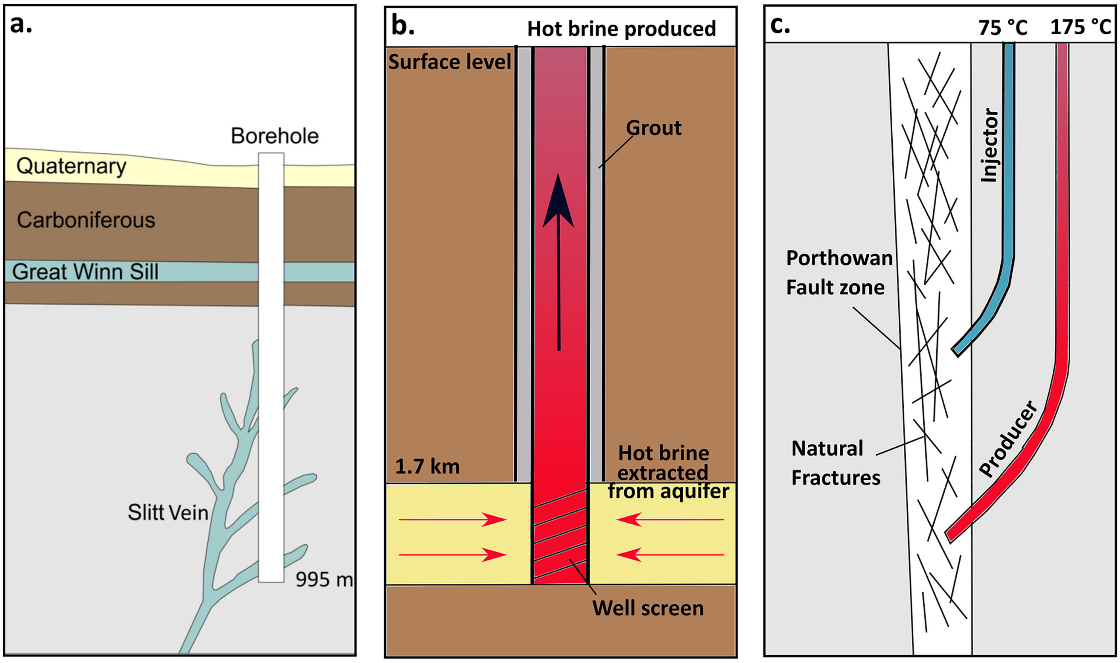

Fig. 2. Schematic diagrams demonstrating (**a**) the Eastgate-1 borehole, (**b**) the Southampton single well geothermal scheme and (**c**) the United Downs Project.

Fig. 3. The Jubilee pool in south-western Cornwall, which is heated by geothermal energy.

associated to the Slitt Vein structure. Further lower permeability fractures were also identified at greater depths. However, these were concluded to be less prolific at feeding fluid into the borehole. The Eastgate-2 borehole was drilled to a depth of 420 m, encountering low permeability, thus, proving the fractures in the Eastgate-1 borehole to be localized to the Slitt Vein. The more recent Newcastle Science Central Deep borehole proved 376.5 m of Fell Sandstone Formation with a thermal gradient of ~37°C/km. However, poor hydraulic conductivity limited further development.

There have been four developments of deep geothermal energy for commercial use to date in the United Kingdom, targeting both conventional and unconventional resources. The first and most successful development has exploited geothermal energy from the Sherwood Sandstone Group within the Wessex Basin in Southampton for over 35 years. The development consists of a single well targeting a ~60-m-thick HSA composed of sandstone to a depth of 1.7 km (Fig. 2b). An average flow rate of ~10 L/s has been producing fluid of 74°C for direct heat use in a district heat network as part of a combined heat and power scheme (CHP).

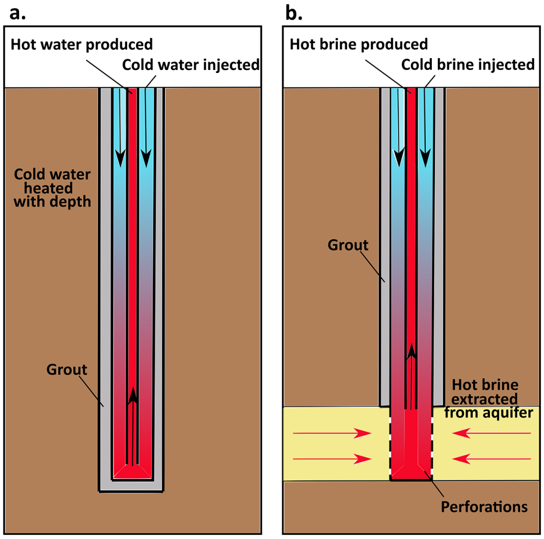

Fig. 4. Schematic of different single well extraction methods: (**a**) is a conventional deep borehole heat exchanger, while (**b**) shows the open standing column/'deep geothermal single well' design.

The three most recent developments target prospects on the south coast of England at the Jubilee Hot Pools, United Downs Project and Eden Project, all of which are in their early stages. The former Jubilee Hot Pools project in Cornwall uses geothermal fluid to warm an open-air swimming pool (Fig. 3). There is limited information on the development in the public domain. The project originally targeted temperatures of 35°C at 1.4 km but the drill depth was limited to 0.4 km.

The United Downs Project (Fig. 2c), used directional drilling of two deep wells targeting the local Porthtowan Fault within the (Permian) Carnmenellis Granite. The production well reached a depth of 5275 m (MD) and the injection well a depth of 2393 m (MD). At present, a binary power plant is being commissioned to exploit 1–3 MW of electricity from geothermal fluids circulated at between 20 and 60 L/s, with a production temperature of ~175°C. The most recent development also targets natural fractures at the Eden Project and has just finished drilling the first.

New technological geothermal development

Recent and past exploration has had limited success due to the high geological risk associated with subsurface permeability, heat stores and fluid presence. Therefore, the limited development of conventional geothermal schemes has subsequently led to the proposition of novel applications of technologies for development. Borehole heat exchangers (BHEs) are not a new concept, having been around since the mid-to-late twentieth century and are frequently used at shallow depths (<300 m). However, few BHEs have been drilled at depths >500 m to help explore their potential in these deeper settings. BHEs limit the geological risk as they can extract heat without fluid interactions between the well and surrounding rocks. Typically, a deep BHE operates using a coaxial system, where a pipe is centred within another pipe—cold fluid is circulated down the surrounding annular space warming with the Earth's natural gradient and is then re-circulated to the surface through the central pipe (Fig. 4a).

Studies in Cornwall have gone further to investigate the potential of a new BHE system with the base of the BHE open as a screened or perforated interval, allowing thermal interactions between the wellbore and reservoir (Fig. 4b). These types of wells are referred to as 'dual model' deep geothermal single wells, or a type of standing column well. During moderate demand periods they allow the well to operate with the same amount of fluid injected as extracted, whilst in high energy demand periods they allow 'bleed' to occur. This allows less fluid to be injected than is extracted, drawing higher temperature fluid from the reservoir, enhancing the thermal power. A study in the United Kingdom has tested this technology at the former Rosemanowes site in Cornwall, and during thermal response tests found thermal power up to ~400 kW can be extracted in a field trial from depths up to 2 km. The system pumped fluid at a rate of 3 L/s with inlet and outlet temperatures of 40°C and 69°C, respectively. Both these technologies are lower in risk as they do not require high-quality hydraulic conductivities and they utilize a single well design, with lower operational and initial costs. Furthermore, there is a significant opportunity to repurpose old oil and gas wells at low costs using the deep closed-loop BHE design.

Modelling of deep borehole heat exchangers in the United Kingdom

Although at present an operational deep BHE in the United Kingdom does not exist, modelling studies of such systems have been undertaken, with recent work in the United Kingdom exploring the potential use of a deep BHE in the Cheshire Basin up to depths of 2.8 km. The Cheshire Basin is a Permo-Triassic basin with a thick clastic succession of sandstones (Fig. 5) and mudstones with basal temperatures expected to reach 100°C. Three-dimensional numerical models were produced to predict thermal changes in the subsurface under varying geological and engineering parameters to model both the impact on seasonal extraction and the lifetime of a system (Fig. 6). Further details on the modelling approach can be found in the *Computers and Geoscience* paper given in the further reading section.

Under optimal conditions, results indicate a thermal power of nearly 300 kW can be produced over a 20-year lifetime, whilst a near quasi-steady state sustainable heat load can be achieved after 4 years. During seasonal extraction, outlet temperature declines exponentially until the surrounding rock and BHE reach a near equilibrium state. The BHE is more efficient at depth where more heat is extracted due to the larger difference in temperature between the circulation fluid and surrounding rock. Different engineering and geological parameters, such as depth of borehole, thermal gradient, volumetric flow rate and thermal conductivity, influence the outlet temperature and heat load.

Fig. 5. Various images of the Helsby Sandstone Formation (Sherwood Sandstone Group) within the Permo-Triassic Cheshire Basin. (**a**) and (**b**) show large scale sections of the formation, whereas (**c**) is a close-up image showing a lithified rootlet. The Helsby Sandstone Formation comprises one key potential geothermal reservoir.

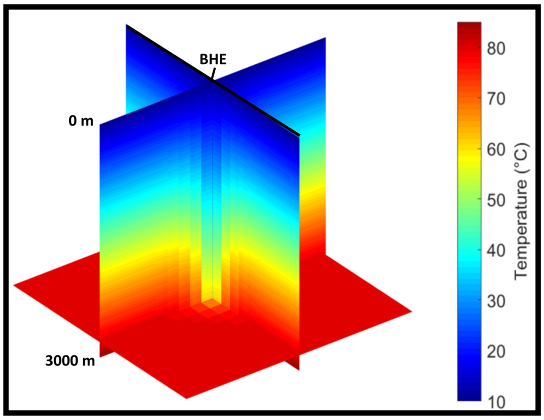

Fig. 6. The 3D numerical model of temperature through a geological section around a BHE.

An opportunity to repurpose petroleum and geothermal exploration wells

In the United Kingdom, there is a legacy of abandoned, plugged or declining oil and gas production wells. These wells provide scope for low-cost repurposing for geothermal extraction using the deep BHE design. Some of the key risks associated with these wells are reduced given that the pressure and subsurface temperatures are known. The deep BHE design will also minimise any risk associated with petroleum fluid interactions. Many companies are looking to use this technology to unlock the geothermal sector, including Egdon Resources for the Dukes Wood-1 well in Nottinghamshire and the Kirklington well in the East Midlands, and CeraPhi Energy and IGas in Lincoln. It has been estimated that 560 out of the 2242 onshore hydrocarbon wells, which were drilled to depths >500 m, could be repurposed in the United Kingdom as conventional resources for geothermal production. However, it is likely that far more can be repurposed in the deep BHE design.

There is a clear need to quantify the potential of this technology in terms of cost-effectiveness of conversion, sustainability and utilisation through whole-systems modelling (i.e., both the subsurface and surface). Existing studies for the United Kingdom are more focused on short-term extraction with homogenous geological design of the subsurface. Long-term modelling based off in situ subsurface data (such as that recovered from thermal response tests) integrated with demand data could be essential to unlocking the potential of technology. Ongoing research aiming to solve some of these questions is currently being undertaken as part of the 'NetZero GeoRDIE' research project. The repurposing of the aforementioned Newcastle Science Central Deep Geothermal well (Newcastle Helix), which was drilled in 2011, to a deep BHE represents one significant case study. During exploration this well proved poor permeability within the Mississippian Fell Sandstone Formation and no option for development as a conventional resource. Some of the current work attempting to retrofit the well as a deep pilot BHE may prove this technology to be pivotal for the future deep geothermal sector in the United Kingdom.

Summary and future outlook

The development of UK geothermal resources is still in its infancy and the emergence of new technology highlights unconventional resources may be exploited with relatively low geological risk. Further study through exploration, testing and modelling could aid with future development, whilst the repurposing of old oil and gas, or geothermal exploration wells add an additional lower cost area for development.

Acknowledgements

We thank Lucy Brown for proof reading, and Richard Charles Brown and Demelza Rose Vinnicombe for supplying photos.

Suggestions for further reading

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