The Development and Deployment of Deep Geothermal Single Well (DGSW) Technology in the United Kingdom

Michael A. Collins[1] and Ryan Law[2]

Deep geothermal heat has not, to date, contributed meaningfully to the overall renewable heat supply in Europe. This is particularly true in the United Kingdom (UK), where there is only one geothermal heat network in operation. This lack of deployment has been due to the geographical distribution of suitable geothermal aquifers, the high cost of drilling to suitable depths, the paucity of deep geological data and, more recently, permitting/ seismicity issues. To enhance the overall development of the deep geothermal resource, Geothermal Engineering Ltd (GEL) and Arup have pioneered the development of single well technology. Progress to date includes a successful field trial in 2014 and the ongoing development of high profile demonstrator projects across the UK via 'Geon Energy Ltd', a joint venture between GEL and Arup.

Les sources géothermales profondes n'ont pas, à ce jour, contribué de façon significative à un gain général et renouvelable de chaleur en Europe. Cela est particulièrement vrai au Royaume Uni (UK) où il n'existe qu'un seul réseau de chaleur géothermale en opération. Ce défaut de développement est lié à la répartition géographique des aquifères géothermaux convenables, au coût élevé du forage pour atteindre les profondeurs requises, le manque de données géothermales profondes et plus récemment, les problèmes concernant les autorisations d'accès et la séismicité. Pour accroître le développement global de la ressource géothermale profonde, les entités Geothermal Engineeering Ltd (GEL) et Arup ont été parmi les premieres à développer la technologie du forage unique. Un progrès marquant inclut un forage d'essai positif en 2014 et le développement en cours de projets de démonstration de haut niveau sur toute la Grande-Bretagne à travers Geon Energy Ltd, un Projet d'Association entre GEL et Arup.

Al día de hoy, el calor geotérmico profundo no ha contribuido de manera significativa al suministro de calor renovable en Europa. Esto es particularmente cierto en el Reino Unido, donde hay solamente una red de calor geotérmico en funcionamiento. Esta falta de despliegue es debida a la distribución geográfica de los acuíferos geotérmicos adecuados, al alto costo de la perforación a profundidades apropiadas, a la escasez de datos geológicos profundos y, más recientemente, a los problemas de permisos y sismicidad. Para mejorar el desarrollo global del recurso geotérmico profundo, Geothermal Engineering Ltd (GEL) y Arup son pioneros en el desarrollo de la tecnología de pozo único. Los avances hasta la fecha incluyen un exitoso ensayo de campo en 2014 y el desarrollo continuo de proyectos de alto perfil en todo el Reino Unido a través de "Geon Energy Ltd", una empresa conjunta entre GEL y Arup.

1. Introduction

According to recent studies (SKM, 2012), the deep geothermal heat resource in the United Kingdom is much greater than the total current annual heat demand. However, the development of deep geothermal energy as a source of renewable heat has been slow. In an attempt to speed up development of the deep geothermal resource, Geothermal Engineering Ltd was funded by the Department of Energy and Climate Change (DECC) in 2013 to design, test and develop so called 'deep geothermal single well' (DGSW) systems, the ultimate aim being to have an *'off the shelf'* technology that can be installed in almost any geological environment, irrespective of permeability. This paper reports on the reasons for the design and development of the single well system, the basic elements of the system, the installation and field trial in an existing deep well and the thermal modelling approaches applied to current projects that the new joint venture company Geon Energy Ltd is working on.

[1] Arup, Scotstoun House, South Queensferry, Edinburgh, EH30 9SE,
[2] Geon Energy Ltd, 13 Fitzroy Street, London, W1T 4BQ
* Correspondance:
mike.collins@arup.com

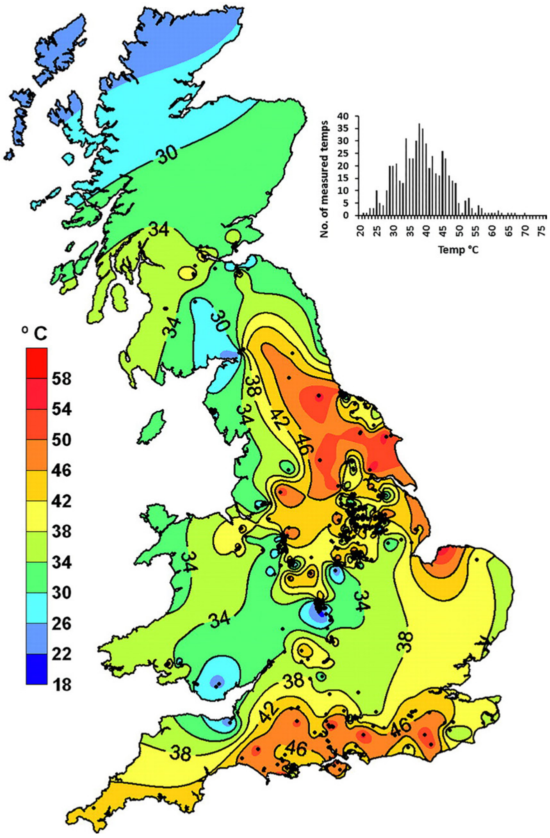
2. Barriers to deep geothermal development in the UK and reasons for the single well concept

There are a number of well-documented reasons why development of deep geothermal resources in the United Kingdom has remained 'largely untapped'. The principal problem is the high risk/ low financial reward associated with deep geothermal heat supply. These barriers are compounded by the lack of knowledge of UK deep onshore geology, an established geothermal industry and the absence of a legal framework. These barriers have meant that, despite a number of deep geothermal heat and power projects being planned over recent years, none have drilled wells and delivered heat or power to an end user or the grid.

For the deep geothermal industry (heat and power) to develop in the UK, there are 5 key constraints that we consider need to be overcome, namely exploration risk, high capital project cost, geographical reach, induced seismicity risk and proximity of heat demand.

3. How the DGSW addresses these issues

Over the past three years, Geothermal Engineering Ltd and Arup have been work-



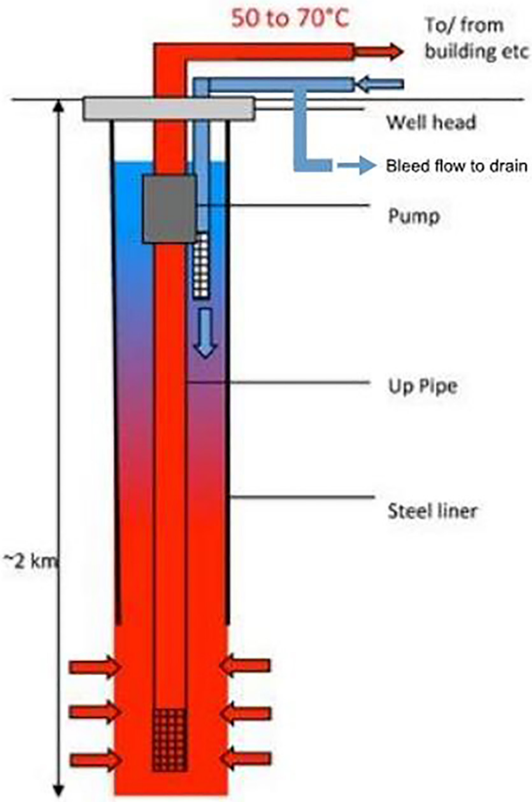


Figure 1: Measured temperatures at 1 km below ground level in the UK (from Busby et al.*, 2011).*

Figure 2: Schematic of the Deep Geothermal Single Well.

ing on the design of a deep geothermal system to address some of the problems that are distinctive to the UK in order to kick-start the delivery of commercially viable geothermal heat. The resulting Deep Geothermal Single Well (DGSW) system addresses each of the challenges listed above in the following ways:

3.1 Exploration risk

The DGSW technology is not dependent on abstracting large quantities of water from the sub-surface. Instead, much like standing column well technology, the majority of the water is re-circulated within the well. This means that a successful project does not rely on identifying, targeting and hitting a highly permeable rock at a specific depth. The only requirement is that the temperature at depth is within the operational range for the building or plant.

A range of temperature at depth maps for the UK have been developed (Busby *et al.*, 2011) which have used deep borehole temperature data sets to create temperature contours to 1 km below the ground surface. These maps indicate that significant areas of the UK have a good thermal gradient (***Figure 1***) that is suited to the circulatory DGSW technology, meaning that renewable heat delivery can be delivered in areas with a heat demand.

3.2 High capital cost per project and delivery times

Drilling single vertical wells substantially reduces the upfront capital expenditure of a deep geothermal heat project. The well design is as simple as possible and the drilling operations run under a Turn-Key contract to reduce cost over-runs. Further, as the DGSW only consists of one vertical well and no plant at the surface, the project delivery time is reduced to between 12 and 18 months.

3.3 Geographical reach

Because the DGSW system is not dependent on a geothermal reservoir (whether existing or artificially created), it has a much greater geographic reach than traditional systems and can be deployed in almost any geological environment where there is a heat demand at the surface. This is important as, in the UK, heat demands are often not located above ideal geothermal conditions.

3.3 Induced seismicity

The DGSW system does not need to inject fluid into the ground at high pressure and does not need to create a reservoir at depth, which is always required in projects utilising doublet systems. In a hard rock such as a granite, some degree of stimulation or 'fracking' will always be required to engineer a reservoir between two wells. The need of fracking for two-well projects leads to costly and lengthy planning and project delays. There is therefore no risk of induced seismicity when a DGSW is installed and no risk of negative community perceptions of the technology.

3.4 Heat demand

The heat output of the DGSW is suited to sites where small heat networks can be developed quickly or are already in place (such as universities, schools, sports centres, multiple apartment blocks, etc.). Larger scale networks with multiple end users are not required. This enables projects to be developed much faster, as the number of parties involved in the Heat Purchase Agreement (HPA) and network operation/ management/ liability is normally one.

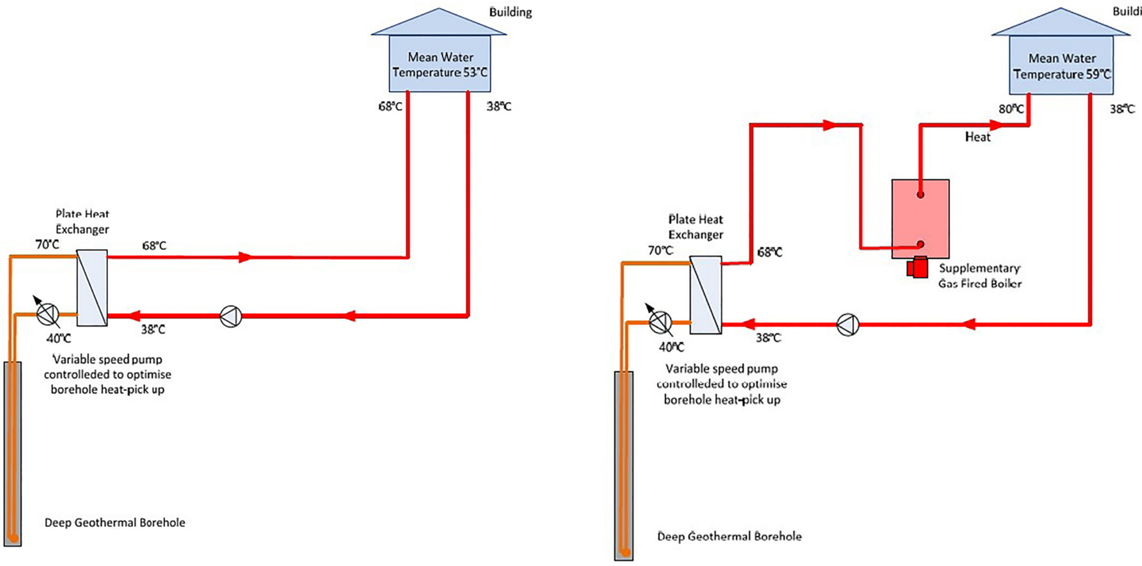


Figure 3: Monovalent and bivalent modes of operation.

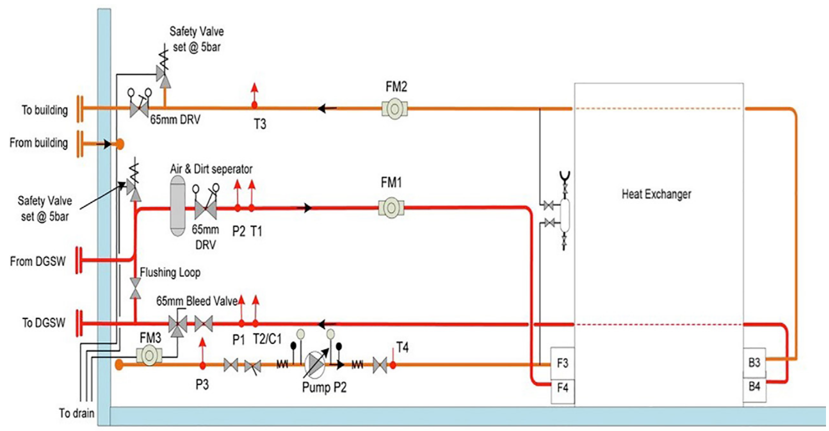


Figure 4: Schematic plan of plant room and heat exchanger connections.

Figure 5: DGSW pipework being installed at the trial site.

4. DGSW system design and operational modes

The DGSW is a simple co-axial design that is similar to that deployed in a standing column well Ground Source Heat Pump system that would typically be found on the East Coast of the United States. The only difference between the two is the materials used for the pipework and the depth of the installation. A schematic of the system is shown in ***Figure 2.***

Figure 6: 400 kW Thermal Response Test (TRT) rig with "air blaster" – external and internal viewpoints.

The system has been designed to operate in two principal modes (***Figures 3 and 4***):

- Monovalent System – DGSW sole source of heat
- Bivalent System – DGSW using gas-fired boilers for supplementary heat

In a standard project, to maximise the thermal output of the DGSW, the operation of existing heating systems would be adapted to run on a lower mean water temperature (MWT) than the norm. The MWT is very well suited to modern buildings that deploy underfloor heating or warm air systems. For retrofits, the secondary circuits will be configured to deliver space heating for longer time periods to accommodate the lower MWT.

5. Installation and field trial

For the field trial, the DGSW equipment was installed in an existing 2.6 km well that was drilled in the granitic rock in Cornwall during the 1980s as part of the Hot Dry Rock project. The pipework was installed and fitted with a fibre optic temperature cable along its length to enable an accurate temperature profile to be recorded every 5 seconds during a range of energy abstraction tests that were carried out on the well (***Figure 5***).

The energy abstraction tests were conducted using a 400 kW 'Thermal Response Test' rig that was designed and built for this project (***Figure 6***).

In brief, a wide-range of tests were conducted on the well, which included flow rate variations, energy abstraction rate variations and durations and 'bleed flow' tests. High quality data was recorded from the pipework installed using a fibre optic cable in the well to enable calculations to be made on the thermal performance of the well under different conditions. The results were also used to validate the numerical models that had been created using the USGS SUTRA code during the design process.

In summary, the field trial proved that the DGSW system could deliver heat with a very high co-efficient of performance (COP). The pump input power was approximately 7 kW to deliver a total flow rate of 3 l/s. The total heat energy output from the well was dependent on the total flow rate, the delivery temperature and the return temperature. With the current configuration, it was shown that a 2 km system would achieve a delivery temperature of 69°C. Using the assumed return temperature of 40 °C, the well would deliver a peak load of 363 kW with a 7 kW input: an equivalent COP of 52.

5. Current projects

5.1 Jubilee Pool, Penzance

One of the first projects will be to develop a deep geothermal single well (DGSW) to supply heat to a portion of the Jubilee Pool, Penzance. The geothermal well will be installed to help attract more visitors to the pool and to assist the wider redevelopment of the area. The deep geothermal work will be partially funded by the European Regional Development Fund (ERDF) and the planning process for the well has recently commenced. The project aims to drill the DGSW in late 2017.

5.2 Aberdeen Exhibition and Conference Centre (AECC)

Geothermal Engineering Ltd, Arup and St Andrews University recently completed a feasibility study for the Scottish Government's *'Deep Geothermal Challenge Fund'* call, which was coordinated through the Scottish Government's Low Carbon Infrastructure Transition Programme (LCITP). The feasibility study (GEL *et al.*, 2016) proposed the installation of a deep geothermal single well (DGSW) demonstrator at the new Aberdeen Exhibition and Conference Centre (AECC) and provided a technical, environmental and economic appraisal of the well delivering heat innovatively to an onsite Anaerobic Digestor (AD) unit.

The site is located on the foliated Aberdeen Granite, which is a substantial pluton-shaped body approximately 16 km in its longest dimension and 6 km in its shortest which was emplaced approximately 470 million years ago (Kneller & Aftalion, 1987).

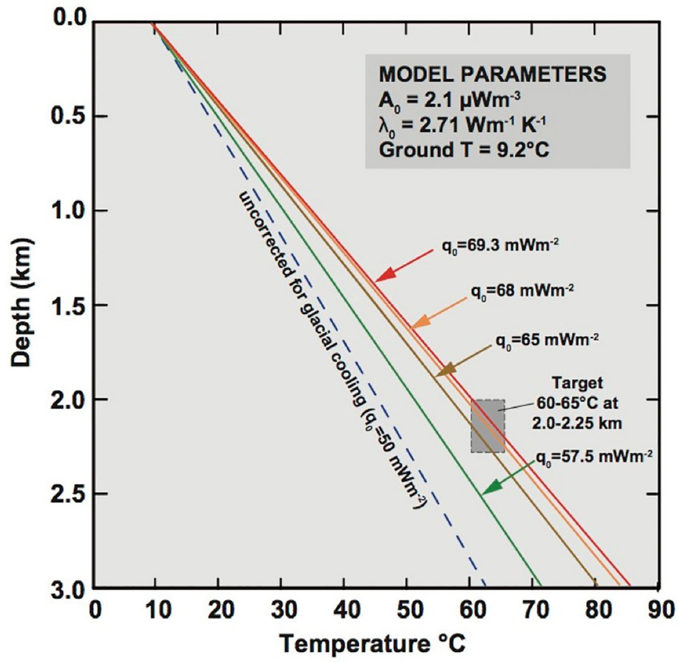


Figure 7: One-dimensional thermal model developed for Aberdeen Granite pluton incorporating surface heat flow q_0 corrections for glacial cooling.

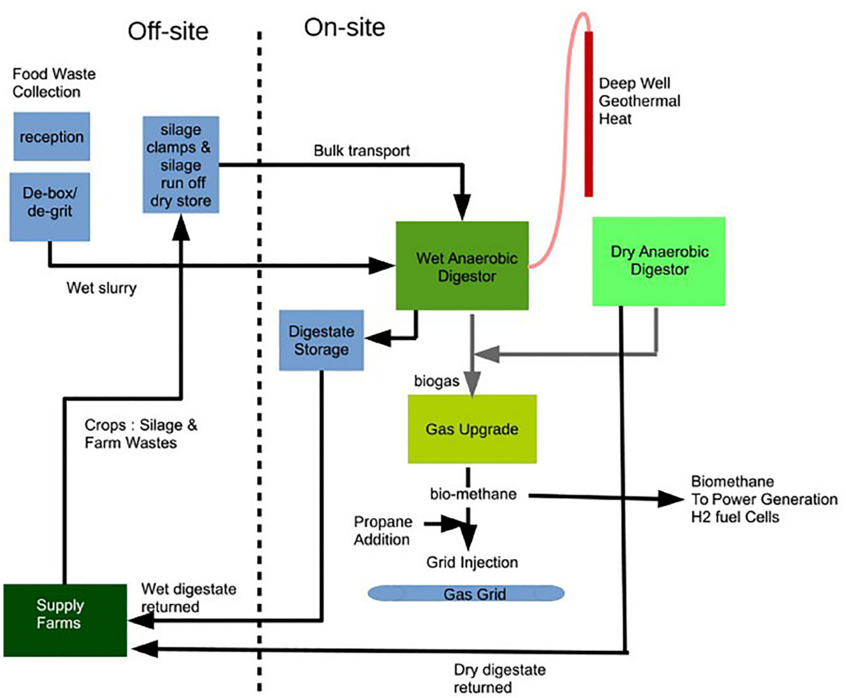


Figure 8: The proposed DGSW integration with the Anaerobic Digestion unit at the new Aberdeen Exhibition and Conference Centre.

In assessing the geothermal potential of the Aberdeen granite, a one-dimensional thermal model was created by St Andrews University following the approach taken by Lee (1986) and Wheildon & Rollin (1986) with the unique difference of taking into account glacial cooling effects on predicting temperature at depth. Recent studies have suggested that surface heat flows q_0 in the NE of Scotland have been underestimated by 15 mWm^{-2} (Majorowicz & Wybraniec, 2011) and 16.8 to 21.7 mWm^{-2} (mean 19.3 mWm^{-2}) (Busby *et al.*, 2015) leading to potential underestimates of thermal resources. Heat production A_0 was estimated from 9 samples of Aberdeen Granite tested for density and presence of the radioactive elements Uranium (U), Thorium (Th) and Potassium (K) using empirical formulae (Rybach, 1988) with a mean value of 2.1 μWm^{-3} used for heat production in the modelling. Four samples of the Aberdeen Granite were tested for thermal conductivity with a mean value of 2.71 Wm^{-1}K^{-1} used for surface thermal conductivity (λ_0) in the modelling.

The graph presented in ***Figure 7*** shows the range of steady state temperature profiles generated in the model outputs based on a range of surface heat flows q_0 and the parameters discussed. The application of q_0 corrections clearly has a significant impact on predicted temperatures at depth within the Aberdeen Pluton.

The DGSW proposal for the Aberdeen AECC is to use the well for the provision of parasitic heat load to the AD plant (***Figure 8***), which would replace the need for a 500kW Combined Heat and Power (CHP) unit. The parasitic heat requirement for the AD unit is for a temperature of between 38-42 °C at 500 kW which, as identified in the modelling undertaken, could be delivered offering the opportunity for 'renewable to heat renewable'. The use of the DGSW would translate to a significant carbon reduction and operational expenditure (OPEX) saving from not needing to import gas for the CHP (c. £1.7 m over a 50 year operational period).

The AECC study also identified a significant opportunity for skills crossover, job creation and supply chain development from the existing oil and gas industry in Aberdeen into deep geothermal development. In particular, the opportunity for synergistic skills diversification was warmly welcomed from the service and supply industries.

The AECC deep geothermal feasibility study has recently completed the third-party technical and economic due diligence which was requested by Scottish Government and it is hoped can form a blueprint for deep geothermal development in Scotland and indeed other locations impacted by glacial cooling.

5.3 The Science Central Borehole (Newcastle University)

The Science Central borehole in Newcastle was drilled to a depth of 1,821 m in 2011 and following significant workover operations including airlifting and recovery testing the target Fells Sandstone formation was reported to have a low conductivity of c. 7x10-5md-1 (Younger *et al.*, 2016) preventing its development as either a demonstration or operational abstracting geothermal well.

In 2016, Arup and Geothermal Engineering Ltd were appointed by Newcastle University to undertake a technical and economic feasibility study on the use of the DGSW technology within the Science Central borehole. Despite the reported low natural permeability, the measured temperature of 73 °C at 1740 m and estimated surface heat flow q_0 of 88 mWm^{-2} (Younger *et al.*, 2016) highlighted that a circulatory deep geothermal system in conjunction with a high temperature heat pump could potentially provide a thermal output from the well that could be used to provide low carbon heat to proposed building units within Newcastle University's Science Central development.

The study included a technical appraisal of the existing well construction, which despite a small 101mm internal well diameter at depth was found to be technically compatible for the installation of the DGSW technology. To evaluate the thermal interaction between the surrounding formation and the well, a two-dimensional axisymmetric model was developed using the USGS SUTRA code. SUTRA was developed to simulate fluid movement and transport of energy in the subsurface environment and can be used to evaluate coupled processes such as fluid density-dependent groundwater flow and transport of thermal energy in the subsurface.

The modelling performed produced likely thermal output ranges for the delivery of heat from the Newcastle well assuming 2 l/s flow (80 to 100 kW) and 3 l/s flow modelled to range between 88 to 138 kW. The models identified that continuous heat delivery over a 24 hr period (with no bleed) would reduce the delivery temperature to approximately 34 °C (***Figure 9***). It was proposed that operating the well for a period of 10 hours per day delivering heat to a building would permit temperature recharge during building non-operational periods, which would have an increased environmental benefit through efficient heat delivery and reduced electricity use.

The results of the evaluations imply that the potential thermal delivery capacity from the well is at least 100 kW at 30 °C (assuming a temperature difference ΔT of 10 °C) and a flow rate of 3 l/s over a period of 10 hours per day. To increase the temperature for use in a building heating system (70 °C), the geothermal well water will require to be passed through a high temperature heat pump. This innovative approach would increase the thermal output of the combined system to be approximately 160 kWh (590,000 kWh/yr).

The study undertaken demonstrated that the installation of the DGSW technology provides a genuine opportunity for the delivery of deep geothermal heat from the Newcastle Science Central well despite the very low natural permeability and the well's technical constraints.

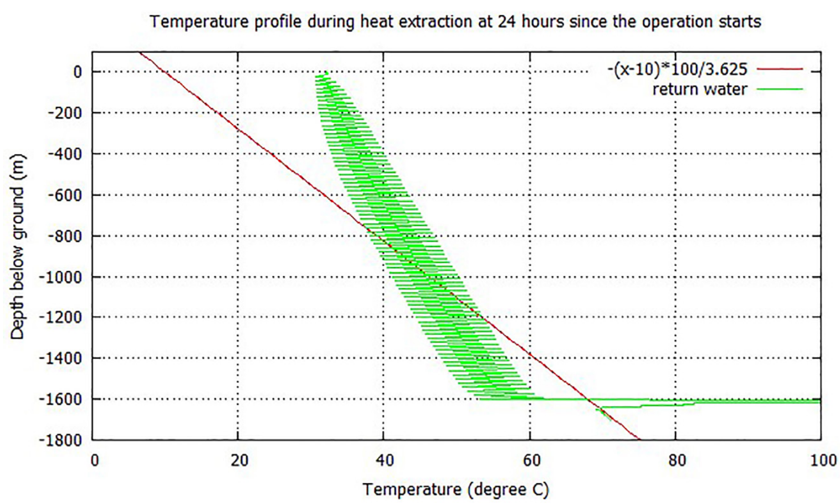


Figure 9: Modelled temperature profile at 24 hrs after heat extraction commences.

5.4 Future Projects

Discussions are currently being undertaken for the utilisation of DGSW heat delivery to a renewable low temperature district heat network project in East Ayrshire in Scotland and also with the School of Geosciences, University of Edinburgh.

6. Conclusions

The Deep Geothermal Single Well system (DGSW) has been developed to kick-start the geothermal heat sector in the UK. It addresses a number of challenges that are distinctive to the United Kingdom.

The system was extensively field trialed in 2014 in an existing deep well in Cornwall. The results showed that, if managed correctly, the system can deliver circa 400 kW with a 7 kW electrical pumping input.

Following on from the trial, a joint venture company has been formed between Geothermal Engineering Ltd and Arup to roll out the technology in the United Kingdom – Geon Energy Ltd. Current projects are ongoing in a range of geological conditions and the paper has described the modelling approaches taken to estimate deep temperature at these sites. Two high profile demonstrator projects are planned for 2017-18 in Cornwall and Scotland with further commercial opportunities to follow.

Acknowledgements

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References

Busby, J., Kingdon, A., Williams, J. 2011. The Measured Shallow Temperature Field in Britain. *Quarterly Journal of Engineering Geology and Hydrogeology*, 44. 373-387.

Busby, J. Gillespie, M., Kender, S. 2015. How hot are the Cairngorms? *Scottish Journal of Geology*, 51. 105–115.

Geothermal Engineering Ltd, Arup & St Andrews University. 2016. Deep Geothermal Single Well (DGSW) Aberdeen Exhibition & Conference Centre Feasibility Report for the Low Carbon Infrastructure Transition Programme (LCITP). ***http://www.gov.scot/Publications/2016/03/9242/0***

Kneller, B. C., Aftalion, M. 1987. The isotopic and structural age of the Aberdeen Granite. *Journal of the Geological Society*, 144. 717–721.

Lee, M. K. 1986. Heat flow. In: Downing, R. A.,Gray, D. A. (eds.) *Hot Dry Rock*. British Geological Survey. pp. 21–41.

Majorowicz, J.,Wybraniec, S. 2011. New terrestrial heat flow map of Europe after regional paleoclimatic correction application. *International Journal of Earth Sciences*,100. 881–887.

Rybach, L. 1988. Determination of heat production rate. In: Haenel, R., Rybach, L., Stegena, L. (eds.) *Handbook of Terrestrial Heat-flow Density Determination*. Dordrecht: Kluwer Academic Publishers. pp. 125–142.

Sinclair Knight Merz (SKM). 2012. Geothermal Energy Potential, Great Britain and Northern Ireland. ***http://www.r-e-a.net/upload/skm_report_on_the_potential_for_geothermal_energy_in_gb__ni_may_2012.pdf***

Wheildon, J. & Rollin, K. E. 1986. Heat flow. In: Downing, R.A., Gray, D.A. (eds.) *Geothermal Energy: The potential in the UK. British Geological Survey*. pp. 8–20.

Younger, P.L., Manning, D.A.C., Millward, D., Busby, J.P., Jones, C.R.C., Gluyas, J.G. 2016. Geothermal Exploration in the Fell Sandstone Formation (Mississippian) Beneath the City Centre of Newcastle Upon Tyne, UK: The Newcastle Science Central Deep Geothermal Borehole. *Quarterly Journal of Engineering Geology and Hydrogeology*, 49. 350–363.