Deep Geothermal Single Well (DGSW)

Aberdeen Exhibition and Conference Centre

Feasibility Report for the Low Carbon Infrastructure Transition Programme (LCITP)

February 2016

GEL

Geothermal Engineering Ltd

University of St. Andrews

ARUP

Ove Arup and Partners

FOREWORD

Professor Iain Stewart

Professor of Geoscience Communication

Plymouth University

Scotland's push for clean, renewable energy means that it is exploring innovative ways to supply heat and power to communities. The exploitation of geothermal energy is one exciting frontier in how our mixed energy future might look. This study proposes a highly innovative approach to utilising our underground geothermal resource by advocating the drilling of a deep geothermal single well for the provision of decarbonised heat supply to the Anaerobic Digestion Plant and also to local dwellings at the proposed Aberdeen Exhibition and Conference Centre.

It is considered that this unique 'two-for-one' demonstrator opportunity at the Aberdeen conference centre will be the perfect opportunity to showcase deep geothermal to the local oil and gas industry (highlighting crossover and supply chain opportunities) and also to educate the public, school children and University researchers on the potential for deep subsurface projects. In that context, it is considered to be the best site in Scotland for the development of a 'deep geothermal exhibition' aimed at improving the public's 'visibility' of the subsurface. Equally, if we are to make deep geothermal happen in Scotland, and across the UK, we need to attract potential investors, and I consider that the low-risk, low-cost DGSW provides that commercial investment platform and opportunity. In summary, this is a great chance to move decarbonised heat supply from the Earth from academic speculation to commercial reality.

SUPPORT – ABERDEEN CITY COUNCIL

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17TH February 2016

Mr Michael Collins
Senior Engineering Geologist
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Dear Mr Collins

Re: Request for support for initial deep geothermal demonstration project

This letter is to confirm Aberdeen City Council is willing to support the initial deep geothermal single well pilot demonstration scheme funding bid being made by Geothermal Engineering Ltd and Arup to the Scottish Geothermal Challenge Fund at the proposed new Aberdeen Exhibition and Conference Centre located in the Bucksburn Area of Aberdeen.

The proposed project to supply renewable low carbon heat is an exciting opportunity for both the local community and wider Scottish interests. The proposed project can help to develop skill and knowledge transfer with the oil and gas industry. The low carbon economy may also potentially strengthen and diversify Scotland's economic base over the coming decade and this project could trigger the beginning of a new industry.

Yours sincerely

Andrew Win
City Development Manager

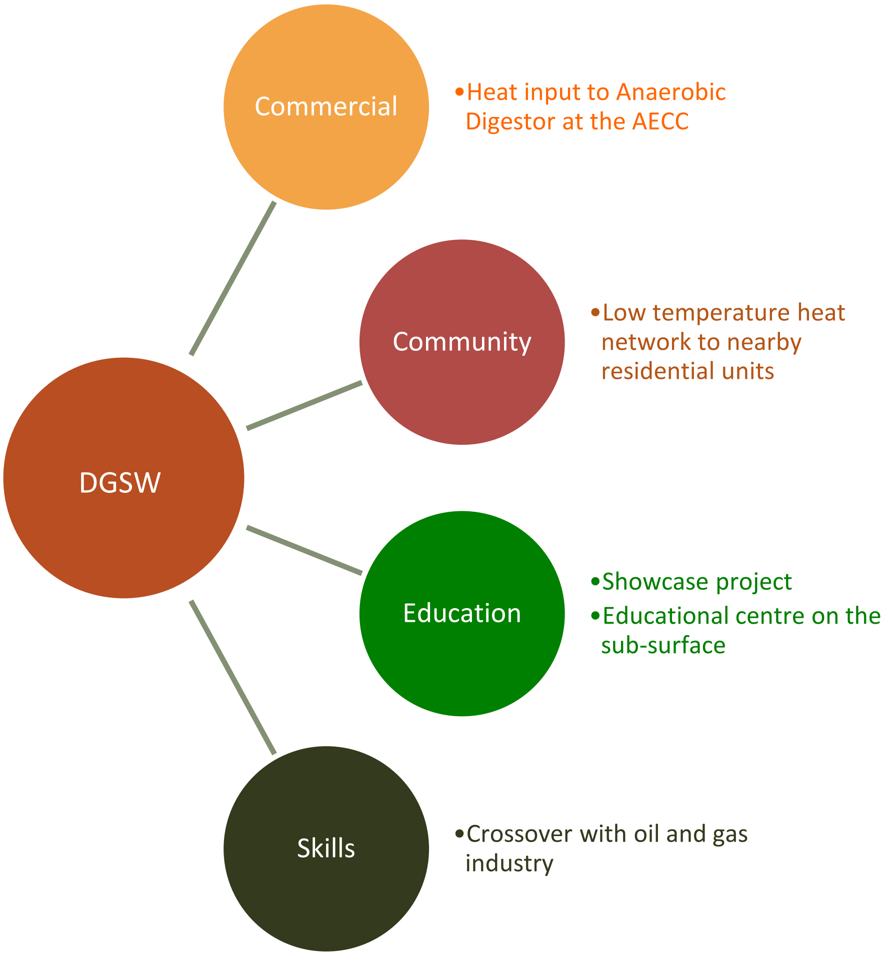
PETE LEONARD
DIRECTOR

GEL ARUP

EXECUTIVE SUMMARY

This study examines the technical, logistical, contractual and economic feasibility of installing a Deep Geothermal Single Well (DGSW) system at the new site of the Aberdeen Exhibition and Conference Centre (AECC). The site offers a unique opportunity for installing a DGSW as it can be used in four ways:

1. To supply low carbon heat to a commercial development (AECC)
2. To supply low carbon heat to nearby residential units using an innovative low temperature heat network
3. Act as a catalyst for deep geothermal energy in Scotland by using the AECC as a showcase project as well as an educational tool for increasing public awareness of the sub-surface
4. Develop cross-over skills with the established oil and gas industry



The DGSW has been developed by Geothermal Engineering Ltd (GEL) to overcome some of the barriers that have hindered the deep geothermal industry in the United Kingdom. The system has been designed to reduce the geological risk, the project delivery time and the cost of delivering deep geothermal heat to buildings. Further, the system does not require 'fracking' or hydraulic stimulation in any form. It is therefore more likely to be acceptable to the public than geothermal projects that involve some form of 'stimulation' techniques. This has recently been demonstrated at an urban site near Crewe where a DGSW project achieved the necessary planning permission and permitting to drill within 3 months and received unanimous public support.

The DSGW consists of a 2km vertical well that is drilled and cased with standard oil and gas equipment. A small submersible pump and an insulated central pipe extending to the base of the well are installed in the centre of the well. Hot water is drawn up through the pipe from the bottom of the well and the heat extracted from the water via a heat exchanger for distribution in the building. The cooler water is then rejected back to the top of the well and descends to the bottom of the well via gravity, heating up on the way before being circulated again. The system has been successfully proven in a field trial in 2014 (funded by the Department of Energy and Climate Change) and delivered 40kW of heat for every 1kW of electricity used in the pump, i.e. an "efficiency" of 4000%. Peak heat outputs from each DGSW are between 400 and 600kW or enough to supply heating to around 200 homes. It is a simple system that, once installed, has no visual impact and can be sited near to the buildings or plant that require heating.

Unlike other types of deep geothermal systems, the DGSW is not overly constrained by the underlying geology and does not rely on the presence of a high permeability, high enthalpy resource. The lack of geological constraint means that the DGSW could be replicated across Scotland. It therefore offers the most realistic method of kick starting the commercial development of a deep geothermal heat sector in Scotland and beyond.

In Scotland, the deep geothermal resource at a depth of between 2 and 3km is sufficient to provide more than enough heat than is realistically possible to deploy in the next 20 years. We therefore believe that limitations to the deployment of deep geothermal heat systems will not be resource constrained but by logistics such as sufficient heat demands at the surface, presence of a network, procurement constraints (buildings in public ownership), drilling rig access, finance and public acceptance.

As the DSGW is vertical, there are no third party ownership issues caused by drilling under other landowners (i.e. no requirements for directional drilling). This is very important in the United Kingdom, as there is no legislation regarding heat ownership and therefore no geothermal licensing framework.

As a demonstration site for the technology, the new AECC development is an exciting location. The site has significant space for drilling, good road access, a good heat demand match and can serve as an international showcase for the technology (and other renewable energy sources) for visitors to the new exhibition and conference centre. As part of the innovative use of renewable sources at the site, it is proposed that the DGSW provides the base heat requirement for the on site anaerobic digester. This would remove the need for an on-site CHP unit and the need to import gas. The return heat flow from the digester will then be used to provide heat for a number of nearby residential dwellings using a low temperature heat network. Therefore, with one demonstrator unit, two sustainable heating uses (commercial and domestic) can be demonstrated simultaneously. We also suggest in this report that the new AECC site could offer the potential of being an interactive 'Deep Geothermal Energy Exhibition' to improve public perception and understanding of the subsurface but also provide a major outreach opportunity for school children to become interested in geoscience and sustainable geo-energy.

The proximity of the new AECC to Aberdeen also means that there is the opportunity to develop a technical and commercial skills crossover with the established oil and gas industry. This report argues that, due to the existing oil and gas skills in Aberdeen, Scotland is in a unique position to be the first mover in the UK in the development of a deep geothermal energy industry and to roll out a commercial and technical deep geothermal supply chain.

We have explored the permitting that would be required for the DGSW at the new AECC site with both the Scottish Environment Protection Agency and Aberdeen City Council and have shared the documentation that we developed for a recent DGSW project at Crewe as guidance. We have also included a section on contracts and insurance, as we believe that these will be important aspects of delivering a successful deep geothermal project on time and on budget.

A financial model and a Lifetime Carbon Assessment (LCA) have also been completed. The LCA shows that, over the lifetime of the plant, the CO2 savings compared to a conventional gas boiler are 22,170 tCO_2e. It is considered that, due to the very high overall efficiency of the system, the commercial roll out of the DGSW could make a significant contribution to aim of decarbonising Scotland's heat supply.

The capital costs for the project are well understood due to recent experience of a similar development in England. Further, they can be well constrained due to the structure of the drilling contracts that would be used on the project. The total cost of delivering the demonstration project at the AECC will be £2.3m.

The commercial appeal of the DGSW is aided by the fact that the system can typically be installed in under 24 months (including planning and permitting). This is significantly shorter than traditional deep geothermal systems. The cost data for the DGSW highlight that compared to traditional deep geothermal systems (which would require directional drilling and more than one well) that it is the lowest cost option available.

The next stage in the development of the project will be to move forward with the permitting and drilling of the well at the site. This would represent a major step forward in the development of deep geothermal heat resources in Scotland and, due to the high profile of the new AECC, attract significant public interest.

Drilling and developing a DGSW at the AECC site will offer a number of benefits:

- Demonstrate that deep geothermal heat can be provided at low risk in Scotland
- Provide a high profile showcase site for deep geothermal heat supply to commercial *and* domestic users
- Offer the opportunity for the creation of a deep geothermal exhibition and education centre.
- Benefit the immediate local community via return flow heating to dwellings
- Provide much needed temperature and geological data from deep on-shore drilling
- Develop a system that does not require fracking or "stimulation". This will be important for ensuring that the local community are on side
- The commercial opportunity for the DGSW and deep geothermal energy in general can be showcased to the widest possible audience
- The location can help to establish cross over and supply chain links between the deep geothermal industry and the oil and gas industry in Aberdeen

RENEWABLE HEAT IN SCOTLAND

In 2015, the Scottish Government released the 'Heat Policy Statement *Towards Decarbonising Heat: Maximising the Opportunities for Scotland*'[1]. This statement identifies that the supply of heat accounts for 55% of energy use in Scotland and is responsible for the largest source of carbon dioxide emissions (47%).

The statement identifies that the key challenges facing Scotland are as follows:

- To decarbonise the heat system by 2050 to reduce greenhouse gas emissions
- To diversify sources of heat generation and supply to reduce reliance on fossil fuels and therefore support a resilient heat supply
- To reduce energy bills through reducing heat demand and providing affordable heat
- To seize the opportunities that this transformation offers through the development of new heat generation, distribution and demand reduction programmes

With the aim of helping to take on the key challenges, the Low Carbon infrastructure Transition Programme (LCITP) was launched in March 2015. In consultation with the Geothermal Energy Expert Group the LCITP started the Deep Geothermal Energy Challenge Fund from which this study was allocated a grant. The Scottish Government has stated that they "would like to see a self-sustaining geothermal energy sector play a significant role in our energy future". The section below discusses the current situation of deep geothermal energy in Scotland, the limited progress to date and how the deep geothermal single well (DGSW) can provide a solution to the development of a commercially viable deep geothermal heat sector in Scotland.

DEEP GEOTHERMAL HEAT IN SCOTLAND

As reported by Aecom[2] in their study on the potential for deep geothermal energy in Scotland (August 2013), '*in Scotland there is little direct evidence at the surface of the vast reservoir of stored heat below and geothermal energy has remained largely untapped*'.

The report split the geothermal heat resource beneath Scotland into three main settings:

- abandoned mine workings (low temperature);
- hot sedimentary aquifers (low and possibly relatively high temperature); and
- hot dry rocks / petrothermal sources (relatively high temperature).

The technology to be discussed in this report (the Deep Geothermal Single Well) aims to deliver heat from two of these resources across Scotland: hot sedimentary aquifers and hot dry/ wet rocks.

REASONS FOR LACK OF DEEP GEOTHERMAL DEVELOPMENT TO DATE

There are a number of well documented reasons why development of deep geothermal projects in Scotland has remained '*largely untapped*'. One of the principal problems is the high risk/ low financial reward associated with deep geothermal heat supply coupled to high up front capital expenditure on drilling. These barriers are not necessarily unique to Scotland but are compounded by the lack of knowledge of deep on shore temperatures and an established geothermal industry. Figure 1 shows the typical risk/ expenditure profile of a typical geothermal project and highlights the difficulties project developers face when they reach

[1] Towards Decarbonising Heat. Maximising the Opportunities for Scotland.
[2] AECOM Investigating Deep Geothermal Potential of Scotland. 2013.

the stage of raising funding for drilling. This usually results in projects stalling (stall point, Figure 1) prior to drilling a well. This is strongly supported by evidence from the United Kingdom over the past decade of deep geothermal development where a number of projects have been planned but not drilled.

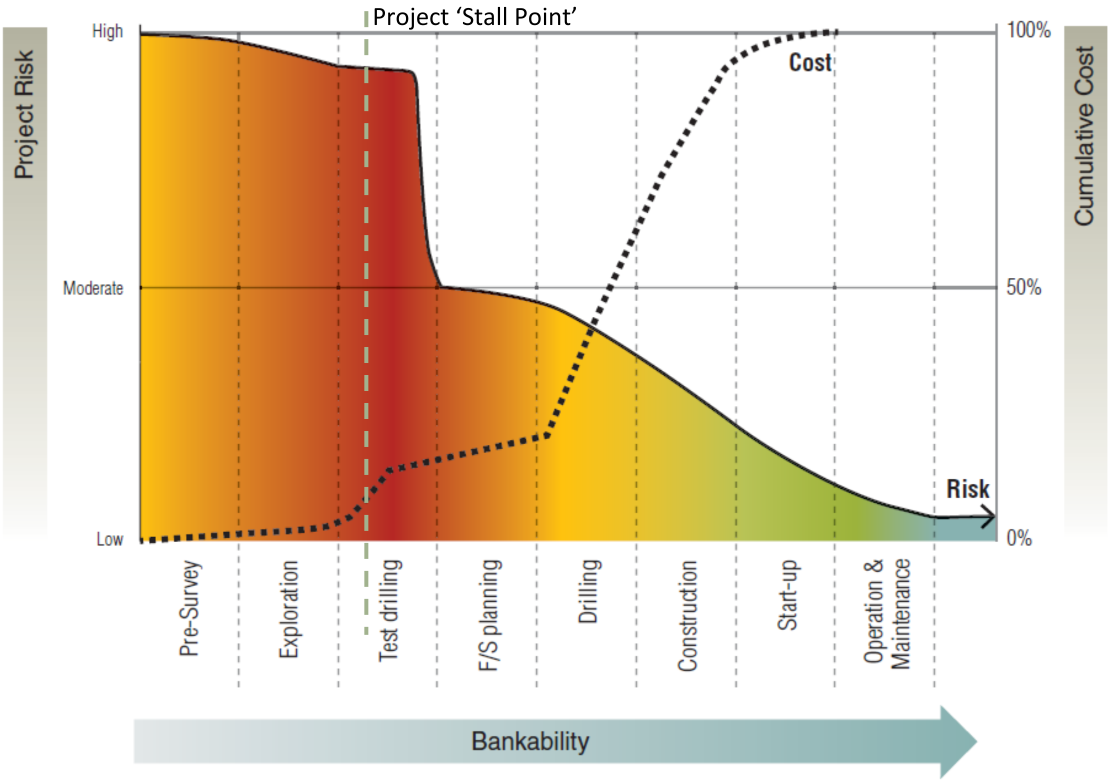


Figure 1: Graphical representation of a typical geothermal project showing risk/ up front capital expenditure (World Bank, 2013)

Compared to other countries within Europe, deep geothermal development in Scotland has been particularly slow, partly due to the relatively low cost of gas throughout the UK from the North Sea. For the geothermal industry (heat and power) to develop in Scotland we believe that the following hurdles will need to be surmounted:

1. Exploration risk

It is common practice to develop deep geothermal heat systems as 'doublet' systems that consist of two wells (one for abstraction and one for re-injection) drilled into a rock that has sufficient permeability to deliver high geothermal fluid flow rates. However, the permeability of the rock (the ability of rock to let water pass through it) and thus the heat or power delivery of the project ***is not confirmed*** until at least one or often both of the wells has been drilled. This means that every project has a high degree of 'exploration risk' whilst at the same time requiring significant capital investment (Figure 1). This is particularly true in countries like Scotland where very few wells have been drilled on-shore to any depth. As the economic returns of a deep geothermal heat project are low, this early stage exploration risk will be a major hurdle to investment.

The only deep geothermal well drilled in the United Kingdom over the last decade is a good example of exploration risk and demonstrates that the permeability of the rock ***is not confirmed*** until the well has been drilled. The Newcastle Science Central Borehole was drilled in 2011 under the lead of Professor Paul

Younger (then of Newcastle University) with the aim of providing deep geothermal heat to the new buildings in the Science Central development. The drilling was grant funded, partly from the Department of Energy and Climate Change. The aim of the project was to target a highly permeable faulted zone in the rock at the target depth of close to 2km. Although the eventual well showed that a good geothermal gradient existed (39C km-1), the measured permeability was two magnitudes smaller than predicted. This meant that the well could not produce anywhere near the required flow rate and the project stopped. This situation exemplifies the risks associated with relying upon the presence of a high permeability aquifer at depth. It also shows that, even if the first well of a doublet system has high permeability, the second well may display very different properties. We do not think that this process should be repeated in Scotland.

2. **High capital cost per project and delivery times**

Without subsidies or other government incentives such as risk insurance, the economics of deep geothermal heat delivery are always marginal. This is mainly due to the high cost of drilling a minimum of two directional wells per project (one for abstraction, one for re-injection). This is particularly true in the UK, where relatively deep wells need to be drilled to reach suitable temperatures for district heating. Up to 80% of the capital cost of a project is associated with the drilling phase and the funding must be allocated to the project a number of years before the heat plant is constructed and the heat delivered. We believe that the delivery time and the capital cost needs to be significantly reduced before private investment will be forthcoming in Scotland.

3. **Geographical reach**

Two well or doublet systems always have to be located above a geothermal reservoir (geological environments where sufficient water and permeability is located underground). Either that, or the reservoir needs to be 'manufactured' by hydraulic stimulation or sheering. Locations where these conditions occur are geographically limited and do not often coincide with the location of a heat load. The geographical reach of doublet systems is therefore limited and unlikely to be able to meet a meaningful proportion of the heat demands across Scotland without significant hydraulic stimulation.

4. **Induced seismicity**

The drilling of a deep two well system within low permeability bedrock such as granites and indeed some sedimentary formations would require hydraulic stimulation or 'fracking' in order to create a permeability pathway for geothermal fluid flow. Normally the deeper the rock, the more difficult it is for water to move through it. A deep geothermal two well system needs to re-inject cooled water back into the rock at relatively high flow rates and under high pressure. Injecting fluids into the ground at depth under pressure has been historically associated with induced seismicity as was recently seen at the Preese Hall shale gas site[3] near Blackpool. It is our belief that the potential for induced seismicity will limit the geographical locations where doublet systems can be installed (i.e. not in urban areas) and may cause significant concern within the local community wherever they are proposed. This aspect of deep geothermal development has not yet been tested in the UK due to the lack of delivery of deep geothermal doublet projects. However, a community backlash to induced seismicity (however small) could severely limit the integration of such systems with urban heat demands.

[3] Preese Hall Shale Gas Fracturing, Green, Styles and Baptie, April 2012

5. **Heat demand**
   Two well systems require multiple megawatts of heat demand to be in place above a location that is suitable for drilling. It is our experience that large-scale heat demands and the associated networks prove difficult and time consuming to develop and are rarely above deep geothermal aquifers. In the short term for Scotland, we think it will be easier to start with smaller scale heat demands (often single owner) so that the network can be planned and managed to suit the geothermal heat supply.

HOW THE DGSW ADDRESSES THESE PROBLEMS

Over the past three years, Geothermal Engineering Ltd has been working on the design of a deep geothermal system to address these problems and kick-start the delivery of commercially viable geothermal heat in the UK. The resulting Deep Geothermal Single Well (DGSW) system has now been extensively modelled and field trialled in an existing deep well as part of a previous project (2014) funded by the Department of Energy and Climate Change (DECC). The system addresses each of the hurdles listed above in the following ways:

1. **Exploration risk**
   The DGSW technology is not dependent on abstracting large quantities of water from the sub-surface (such as the Newcastle Well). Instead, 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. This ***significantly reduces the exploration risk*** associated with a project, as the temperature at depth is much better understood than the permeability, which can vary by orders of magnitude between different wells.

2. **High capital cost per project and delivery times**
   Drilling narrow diameter single vertical wells substantially reduces the upfront capital expenditure of a deep geothermal heat project. The total capital cost of a commercial DGSW system will be between £1.5m and £2.5m, compared to greater than £14m for a directionally drilled doublet system (£7m per well) that requires directionally drilled wells. Further, as the DGSW only consists of one vertical well and no plant at the surface, the project delivery time can be reduced to between 12 and 24 months. The combination of low risk, short delivery times and reduced capital expenditure means that different funding routes can be pursued for these sorts of projects, such as community Crowdfunding. The simple vertical well design also enables turnkey contracts to be developed that reduce the risk of cost over-runs to the developer.

3. **Geographical reach**
   Because the DGSW system is not dependent on geothermal reservoirs, that are geographically restricted in the UK, 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 heat demands are often not located above ideal geothermal conditions. The small footprint also means that it is well suited to urban areas and therefore has a more realistic chance of supplying heat to existing end users than larger scale systems.

4. **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. There is therefore ***no risk of induced seismicity*** when a DGSW is installed and no risk of community backlash. This is very important when trying to develop a new commercial industry. The

recent induced seismicity at a shale gas site in England caused a two year delay to the entire industry whilst the Government investigated the incident.

5. **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 and network operation/ management/ liability is normally one. Given the relatively small number of large-scale heat networks in place in Scotland, the DGSW can be rolled out to many areas that do not have such networks and will, realistically, never have them developed. This is particularly relevant to rural zones that have never even been connected to gas grid networks.

PURPOSE AND SCOPE OF THE STUDY

The scope of this study is to provide a techno-economic assessment for the installation of a Deep Geothermal Single Well (DGSW) at the new Aberdeen Exhibition and Conference Centre. The installation of the DGSW will provide deep geothermal heat from a 2km well drilled into either hot dry rock or hot wet rock (depending on the geology encountered when the well is drilled to target depth). The study encompasses a geological and geochemical assessment of the site in conjunction with Arup and St. Andrews University and evaluates the economics, permitting, logistics and contractual issues related to the proposed installation. Like all deep geothermal projects in Scotland, the geology will not be known at depth until the well is actually drilled. The primary aim of this report is to provide the detail to support the economic case for funding the next stage of the project: permitting, drilling the well and installing the system.

METHODOLOGY AND PROJECT PARTNERS

Geothermal Engineering Ltd (GEL) has led the project with support from project partners Arup and St. Andrews University. GEL has previous project experience (2014) of installing and testing the DGSW equipment in an existing 2.6km well in igneous granite in Cornwall as well as developing geothermal projects around the world. The company is also in the process of obtaining permitting and agreeing contracts for a 2km DGSW system at the Crewe Campus of Manchester Metropolitan University supported by Arup (a project part funded by the Department of Energy and Climate Change). The team therefore has a very good understanding of the practicalities, contracts, permitting, logistics and costs of progressing with this type of project. For this report, GEL has focused on describing the technology, the expected permitting requirements, installation and integration issues, contracts and the financial aspects of the DGSW. St Andrews has substantial knowledge of the granitic rocks in Scotland and is the logical choice for evaluating the rock type, geochemistry and temperature that are most likely to be found at the target depths. Arup have provided input into the geological setting at the site and have provided support in all areas of the project, in particular on planning, public perception, oil and gas synergies and building integration methodologies.

GEOLOGY AT THE SITE

GENERAL GEOLOGICAL SETTING

A review of the available drift and solid British Geological Survey (BGS) geological maps has been undertaken. The site falls within drift geology map NJ81/91 (1:25,000)[4] and solid geology map and NJ81SE (1:10,560)[5].

SUPERFICIAL GEOLOGICAL MAP

The superficial geology map[1] indicates the site to be predominantly underlain by till described as:

"*Mainly yellowish brown sandy diamicton with clasts of Dalradian metamorphic and Caledonian igneous rocks, derived locally or from a short distance to the west, Matrix weather in part and containing much decomposed (grussified) rock."*

Some areas in the central and southern part of the site are shown to be underlain by alluvium described as: *Gravel and sand, capped by silty and clayey floodplain deposits*. Based on the fact that the location of these areas is in close alignment with the existing water courses on the site it is thought that the indicated alluvium is associated with material carried by the Green Burn, Gough Burn and the East Craibstone Burn. Some localised areas between the current Rowett Institute and the south-western boundary of the site are indicated to be underlain by made ground. The key indicates the made ground to be: *Mainly spoil associated with sand and gravel workings.*

There are localised areas in the southern part of the site are shown to be underlain by glacio-fluvial ice contact deposits – *moundy deposits of sand and gravel*. One of these areas is indicated to underlay a large area of the Rowett Institute.

SOLID GEOLOGICAL MAP

The solid geological map[2] for this area shows that the solid geology underlying the entire site comprises of Vein Complexes and Plutonic Igneous Rocks of the Aberdeen and Kemnay Plutons with foliated biotite-muscovite-granite. An exposure approximately 1km to the north-west of the site describes the granite to be "*well foliated medium grained granite – sometimes biotitic schlieren".*

The depth of the underlying rock is not indicated. However, the superficial geology map indicates bedrock to be near or at the surface in areas approximately 0.7km to north, 0.5km to south east and 1.0km to east. The bedrock at or near the surface is described to be: *Locally weathered to sand or micaceous silty sand (gruss) to depths >2m, especially in the west* (of the area covered in the geology map). A solid geological boundary with Metamorphic Psammite of the Argyll Group is identified approximately 1km to the west of the site.

[4] BGS Geological Map NJ81/91 (1:25,000)
[5] BGS Geological Map NJ81SE Solid Geology (1:10,560)

HYRDOLOGY AND HYDROGEOLOGY

A number of surface watercourses cross the site. These include the Green Burn, Gough Burn and East Craibstone Burn. These watercourses flow eastwards into the River Don, which is located approximately 600m to the east of the site and is identified by SEPA to be of moderate quality. The most recent groundwater vulnerability map produced by SEPA[6] shows that the area in which the site is located is classified as vulnerability class 2, but classifications 1 and 3 are also within close vicinity of the site. Using the accompanying report "*Vulnerability of Groundwater in the uppermost aquifer*"[7], the site can be characterised as "*Vulnerable to some pollutants, but only when they are continuously discharged/leached*".

SEPA have also produced maps of the superficial and bedrock aquifer Productivity[4]. The superficial aquifer productivity map indicates that the site may have areas of very low to high productivity and that the flow is inter-granular. The solid aquifer productivity map shows that the bedrock has a very low productivity with fracture flow. An Indicative River & Coastal Flood Map, produced by SEPA[8], classifies areas along the Green Burn as "*area at risk of flooding from rivers*". The current groundwater vulnerability map has been reviewed and [9] represents the vertical pathway of groundwater through strata overlaying an aquifer. Groundwater vulnerability is defined as the tendency and likelihood for general contaminants to reach the water table after introduction at the ground surface. The most recent vulnerability map indicates that the site is generally located in an area classed as moderately permeable, with a geological classification as follows: *Minor or Moderately Permeable Aquifer - Fractured or potentially fractured rocks which do not have a high primary permeability or other formations of variable permeability*.

PREVIOUS ENGINEERING GROUND INVESTIGATIONS (AECC PRELIMINARY GROUND INVESTIGATION 2014)

In 2014, Arup were appointed to perform a preliminary geotechnical ground investigation at the proposed AECC site in Aberdeen[10]. The intrusive investigations performed by Raeburn Drilling & Geotechnical Ltd. encountered the following ground conditions (Table 1) at the site included rotary cored boreholes.

Stratum Description	Depth to top of stratum (m)	Depth to base of stratum (m)	Level of the top of stratum (mAOD)	Level of the base of stratum (mAOD)	Proven thickness (m)
Topsoil	0	0.1 – 0.5	48.64 – 77.17	48.34 – 76.87	0.1 – 0.5
Made Ground[a]	0 – 0.5	0.7 – 3.4[b]	52.73 – 62.56	51.98 – 61.96	0.6 – 3.3
Possible Alluvium[c]	0.1-0.3	0.7-0.75	51.20 – 58.43	57.98 – 50.70	0.45 – 0.6
Glacial Deposits	0.1 – 2.6	7.7 – 21.1[d]	48.37 – 76.87	35.62 – 53.52[d]	7.25 – 20.6[d]
Bedrock	7.25 – 20.6	Proven to between 12.2 and 30.1mbgl	35.62 – 53.49	Proven to between 26.76 and 49.42mOD	Proven to between 4.1 and 9.7m

Table 1 Stratigraphy of the site

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[6] British Geological Survey, O' Dochartaigh et al, *User Guide: Groundwater Vulnerability (Scotland) GIS dataset, Version 2. British Geological Survey Open Report, OR/11/064.* 2011.
[7] British Geological Survey, O' Dochartaigh et al, A *GIS of aquifer productivity in Scotland: explanatory notes, CR/04/047N*. 2004.
[8] Scottish Environment Protection Agency, Indicative River & Coastal Flood Map (Scotland).
[9] Landmark Information Group Ltd, Envirocheck Report for The Rowett, Aberdeen City (21st January 2014).
[10] Raeburn Drilling & Geotechnical: Factual Report on Intrusive Ground Investigations. 2014.

Note: Hand dug trial pits have not been considered in the above assessment.
[a] Made ground was only encountered in exploratory holes BH07, BH08, TP13-TP16,TP19-TP20 as well as a number of the hand dug trial pits.
[b] The thickness of the made ground was not proven in TP14 and TP20, where made ground was recorded to the base of pits, 3.0 and 3.4mbgl respectively.
[c] Possible alluvium was only encountered in BH08A, TP12 and TT02.
[d] Base of the glacial deposits were only proven in boreholes BH02, BH02A, BH05, BH05A, BH06C, BH08 and BH09. Only these boreholes have been used in the assessment of the glacial deposit base and thickness.

DESCRIPTION OF BEDROCK GEOLOGY

Bedrock was encountered in all of the exploratory positions where rotary drilling was undertaken. The bedrock comprised of granite in all of the exploratory locations. The granite was typically described as distinctly weathered and often recovered as non-intact (sand and gravel).

Rotary coring of the granite was undertaken using triple tube techniques, however; in a number of boreholes the recovery of the granite proved poor (particularly the upper few metres) likely due to the heavily weathered nature of the rock. Coring between 4.1 and 9.7m of the granite bedrock was attempted in the boreholes. The weathering of the bedrock was noted to decrease with depth in some of the boreholes.

Typical descriptions of the granite included:

"Very weak massive coarse grained brownish orange GRANITE. Granite is distinctively weathered with a penetrative staining ~3mm throughout rock, clay on fracture surfaces and loss of strength. Rock is weathered to a coarse gravel in places. There are 2 fracture sets. #1 closely spaced, sub-horizontal, rough, planar. #2 closely spaced, dipping 70°-90°, rough, planar" (BH02A)

"Very weak and weak massive speckled yellowish off white GRANITE. Distinctly weathered evident as clay smears on fracture surfaces, yellow discolouration and loss of strength throughout. There are 3 fracture sets. #1 medium spaced, sub-horizontal, planar and rough. #2 close and medium spaced, dipping at ~45°, planar and rough. #3 closely spaced, dipping at ~10°, stepped and rough." (BH05)

"Very weak to strong massive speckled black and white GRANITE. Distinctly weathered evident as yellowish brown discolouration penetrating up to 5mm, clay smears on fracture surfaces and loss of strength throughout. There are 3 fracture sets. #1 close and medium spaced, dipping at ~45°, planar and rough. #2 medium spaced, dipping at ~70°-90°, stepped and rough. #3 very close to medium spaced, dipping at ~ 50°, planar and rough. Locally recovered non-intact where fracture sets meet. Weathering decreases with depth" (BH09).

Engineering tests have been performed on samples of the cores obtained from the 2014 investigations. A review of the laboratory strength test results indicate that the corrected point load index, $Is_{(50)}$, values typically range between 0.02kN/m² and 3.04kN/m². A calibration exercise was carried out to select an appropriate factor for the $Is_{(50)}$ to unconfined compressive strength (UCS) correlation factor and 10 was found to be an appropriate value. The results would indicate the strength of the granite to be between 0.2kN/m² and 30.4kN/m²; thus indicating the granite to be below 'extremely weak' to 'medium strong'. Average $Is_{(50)}$ values indicate that the granite is typically 'weak'.

UCS tests were also undertaken on samples of granite and indicate granite to vary between 'very weak' to 'medium strong' and to be 'weak' on average. There appears to be some correlation with the strength of the granite and depth, however, extremely weak granite was also encountered well below the rockhead.

Geotechnical Property	Unit	No. of tests	Range	Mean
Point Load Index	Is50	37 Axial	0.02 – 3.04	0.73
		38 Diametral	0.02 – 2.61	0.63
		12 Lump	0.05 – 0.52	0.25
Derived UCS (converted from Is50 using a factor of 10) [18]	MPa	37 Axial	0.2 – 30.4	7.3
		38 Diametral	0.2 – 26.1	6.3
		12 Lump	0.5 – 5.2	2.5
Uniaxial Compressive Strength	MPa	10	2.2 – 26.5	15.6
pH	-	10	7.6 – 8.5	8.1
Sulphate (2:1 extract)	g/l	10	<0.01 – 0.04	0.015*

Table 2: Summary of Measured Geotechnical Properties – Granite

*Tests recording '<0.01' of sulphate were assumed as 0.01g/l.

ABERDEEN GRANITE COMPOSITION AND EXPECTED GEOLOGY TO 2KMS

The Aberdeen granite is a substantial pluton-shaped body approximately 16km in its longest dimension and 6km in its shortest with the long axis aligned approximately NNW-SSE (Figure 2). It was emplaced approximately 470 million years ago, based on ages obtained from monazites in samples from the Rubislaw quarry and dated by the U-Pb method (Kneller & Aftalion, 1987)[11]. Textural relationships indicate that the granite was emplaced into Dalradian host rocks at peak temperatures of circa 550°C and a pressure of 0.50-0.55 GPa (Harte & Hudson, 1979.)[12]. This implies that the present surface of the granite was located some 17-20 km below the surface at the time of metamorphism and magmatism. Such deep emplacement is also implied by the lack of a thermal metamorphic aureole (Munro, 1986)[13]. The age of the granite, along with geochemical characteristics, indicate that the pluton does not belong to the younger Cairngorm suite of Newer granites of late Silurian-early Devonian age (Stephens & Halliday, 1984)[14] that were the focus of study in the 1970s and 80s for their geothermal potential (Downing & Gray, 1986)[15].

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[11] Kneller, B. C. & Aftalion, M. (1987). The isotopic and structural age of the Aberdeen Granite. *Journal of the Geological Society* **144**, 717-721.
[12] Harte, B. & Hudson, F. C. (1979.). Pelite facies series and the temperatures and pressures of Dalradian metamorphism in E Scotland. In: Harris, A. L., Holland, C. H., Leake, B. E. (eds.) *The Caledonides of the British Isles-reviewed*. London: Geological Society, 323-337.
[13] Munro, M. (1986). *Geology of the country around Aberdeen*: British Geological Survey.
[14] Stephens, W. E. & Halliday, A. N. (1984). Geochemical contrasts between late Caledonian granitoid plutons of northern, central and southern Scotland. *Transactions Royal Society Edinburgh: Earth Science* **75**, 259-273.
[15] Downing, R. A. & Gray, D. A. (1986). *Geothermal energy: the potential in the United Kingdom*: British Geological Survey.

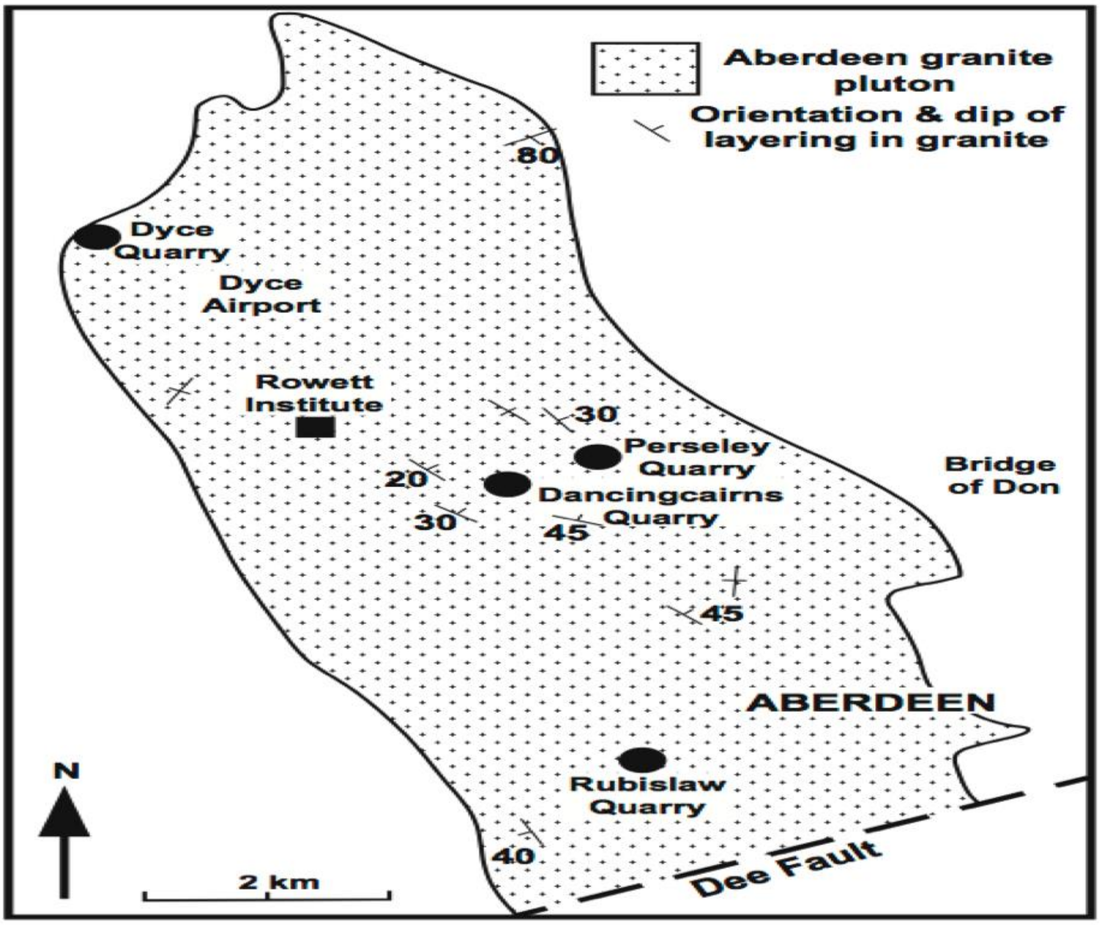

Figure 2. The Aberdeen Granite Pluton

Whole rock geochemistry, including stable and radiogenic isotopes strongly implicates metasedimentary material similar to the host Dalradian Supergroup rocks as the dominant source material for these granites (Halliday *et al.*, 1979[16], Kay, 1980[17]). This is consistent with several other characteristics typical of S-type granites (Chappell & White, 2001[18]).

FORM OF THE ABERDEEN GRANITE

The outer contacts of the granite pluton are generally obscure, largely because outcrop is poor. The available evidence indicates inter-digitation with the local biotite gneisses, implying that a plexus of granite sheets petrographically similar to the pluton was injected into metasediments adjacent to the contact. These sheets are often some 10-15m thick and tend to be relatively flat lying (Munro, 1986). Although no evidence has been found to constrain the dip of the plutonic granite-metasedimentary contact at any locality, it is relevant that, on a larger scale, the contacts cut across all lithological units and structures suggesting that the interior of the body at least has the form of a single pluton with relatively steep outer contacts inside the sheeted

[16] Halliday, A. N., Aftalion, M., van Breemen, O., Jocelyn, J. (1979). Petrogenetic significance of Rb-Sr and U-Pb isotopic systems in the 400 Ma old British Isles granitoids and their hosts. In: Harris, A. L., Holland, C. H., Leake, B. E. (eds.) *The Caledonides of the British Isles-reviewed*. London: Geological Society, 653-662.
[17] Kay, L. (1980). Oxygen and hydrogen isotope ratio study of Caledonian rocks from northeast Scotland (PhD thesis). University of Aberdeen.
[18] Chappell, B. W. & White, A. J. R. (2001). Two contrasting granite types: 25 years later. *Australian Journal of Earth Sciences* **48**, 489–499.

margins. This is supported by the relative homogeneity of the pluton interior compared with the more nebulitic margins. The Rowett site for the new AECC is closer to the centre of the granite than the outer contact of the Aberdeen granite and at depths of around 2km it is most likely that the site will be underlain by broadly similar granite belonging to the same pluton.

Some granite plutons in the eastern Grampian Highlands, including Cairngorm, Lochnagar, Glen Gairn and Mount Battock, are associated with a large negative Bouguer gravity anomaly bounded by the -40 mgal contour) stretching from Cairngorm in the west for about 80 km eastwards (BGS, 2007[19], Rollin, 1984[20], Wheildon et al., 1984[21]). This substantial anomaly is modelled as a single batholith extending to depths of at least 10 km. The Bouguer anomaly tails off as it approaches Aberdeen but small kinks in the regional trend may reflect the presence of a weak anomaly associated with the Aberdeen granite. Density measurements give means of 2800 ±157 and 2740 ±99 kg m^{-3} (both 2 sigma) respectively for regional Dalradian and Moine rocks (Richardson & Powell, 1976[22]). The Dalradian mean density value falls within the 2650-2950 kg m^{-3} range (mean=2740) previously determined for 80 specimens of Dalradian rocks in Aberdeenshire (McGregor & Wilson, 1967[23]). The density of the Aberdeen granite falls within the same range, values varying from 2673 to 2688 (mean=2678 kg m^{-3}, standard deviation of 7). This overlap in the density of the granite and its host rocks is consistent with the widely accepted view that similar rocks to the regional Dalradian were the source of much of the Aberdeen pluton however this lack of density contrast weakens the usefulness of gravity modelling for predicting the structure of the pluton at depth.

STRUCTURAL FEATURES

Structural features in the granite may facilitate heat replenishment at the base of the column by facilitating the advective transfer of fluids. The potential geothermal roles of foliations, joints and faults in the Aberdeen granite are described below.

The Aberdeen granite is variously foliated. A strong foliation, defined principally by the planar alignment of biotite and feldspar crystals, has a tendency to follow the orientation of the local country rocks at the contact but on a larger scale this foliation is discordant with the host formation. This evidence along with petrographic textures suggests that this mineral foliation is a primary magmatic feature formed during consolidation of the pluton (Munro, 1986). The dip of the primary foliation varies from 20° to vertical in outcrops relatively close to the Rowett site. Post-consolidation recrystallisation has affected the magmatic foliation as evidenced by textural features and crystallographic evidence of strain in quartz grains. This recrystallisation is not pervasive; recrystallized and unaffected material may occur in the same outcrop and even sometimes in the same thin section (Munro, 1986). In thin section neither of these foliations appear to create open pathways suitable for fluid flow but conditions may be more suitable for opening up these foliations at 2km depth, perhaps through the alteration of micas. Even so, the probability of high permeabilities created in this way is likely to be relatively low.

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[19] BGS. (2007). Gravity Anomaly UK North. British Geological Survey (NERC).

[20] Rollin, K. E. (2984). Gravity modelling of the Eastern Highlands granites in relation to heat flow studies. *Investigation of the geothermal potential of the UK*. Keyworth, 17pp.

[21] Wheildon, J., King, G., Crook, C. N., Thomas-Betts, A. (1984). The Eastern Highlands granites: heat flow, heat productionn and model studies. *Investigation of thegeothermal potential of the UK*. Keyworth, 40pp.

[22] Richardson, S. W. & Powell, R. (1976). Thermal causes of the Dalradian metamorphism in the central Highlands of Scotland. *Scottish Journal of Geology* **12**, 237-268.

[23] McGregor, D. M. & Wilson, C. D. V. (1967). Gravity and magnetic surveys of the younger gabbros of Aberdeenshire. *Quarterly Journal of the Geological Society of London* **123**, 99-123.

Joint planes are ubiquitous in granites such as that found at Aberdeen. The only site where these have been investigated formally is at Perseley Quarry in an early study of joint patterns (Cameron, 1945[24]). Here, the principal joint set runs parallel to the primary foliation (described above) that at this locality is essentially vertical. From a quarry in the neighbouring Kemnay granite pluton, Cameron identified a strong horizontal joint set that he attributed to the erosion of overlying rocks. Descriptions of bedrock from shallow rotary drill cores at the Rowett site include the recognition of both sub-vertical and sub-horizontal fracture sets suggesting that these joint orientations may be common throughout the pluton and the vertical set may be anticipated at 2km depth. However, if the horizontal set is related to roof unburdening then it may not be well developed at depth. If such a sub-vertical joint set were well developed at 2km depth below the Rowett site these joints might facilitate vertical upward flow of warmer fluids from depth. **Drilling a 2km vertical well at the site would represent an excellent opportunity to test this theory and the presence of vertical upflow and will substantially increase the thermal output of the well.**

Major faults are few, similarly very few small faults have been mapped over the granite pluton. The only fault of importance is the post-Devonian Dee Fault that defines the southern border of the Aberdeen granite but this is some distance from the Rowett site.

PETROLOGY

The principal granite facies over the whole Aberdeen pluton is grey muscovite biotite granite which occasionally appears pink or red when associated with alteration and joint planes. It is normally medium grained (1-3mm) and equigranular (Figure 3a). Variation in facies is usually related to coarser grained varieties (sometimes pegmatites) and banded schlieren (Munro, 1986). Enclaves are common, most typically these are metasedimentary xenoliths likely to be fragments of country rocks, while only occasional samples are mafic enclaves of more primitive origin.

Quartz is particularly abundant in these granites (33-36%) with plagioclase in the same range and somewhat less alkali feldspar (20-23%) while the micas amount to 6-11% with biotite predominating over muscovite (Munro, 1986). The rocks classify as true granites or granodiorites. Plagioclase shows normal and oscillatory zoning with albitic margins and the grains are often altered. Alkali feldspar usually shows patches of microcline twinning (Figure 3a) and large quartz grains usually take the form late interstitial crystals (Figure 3b) while small grains of quartz are found in myrmekites and as inclusions in feldspars. Ragged brown biotite grains that often define the primary foliation are often associated with later muscovite (Figure 3c).

[24] Cameron, J. (1945). Structural Features of the Grey Granites of Aberdeenshire. *Geological Magazine* **82**, 189-204.

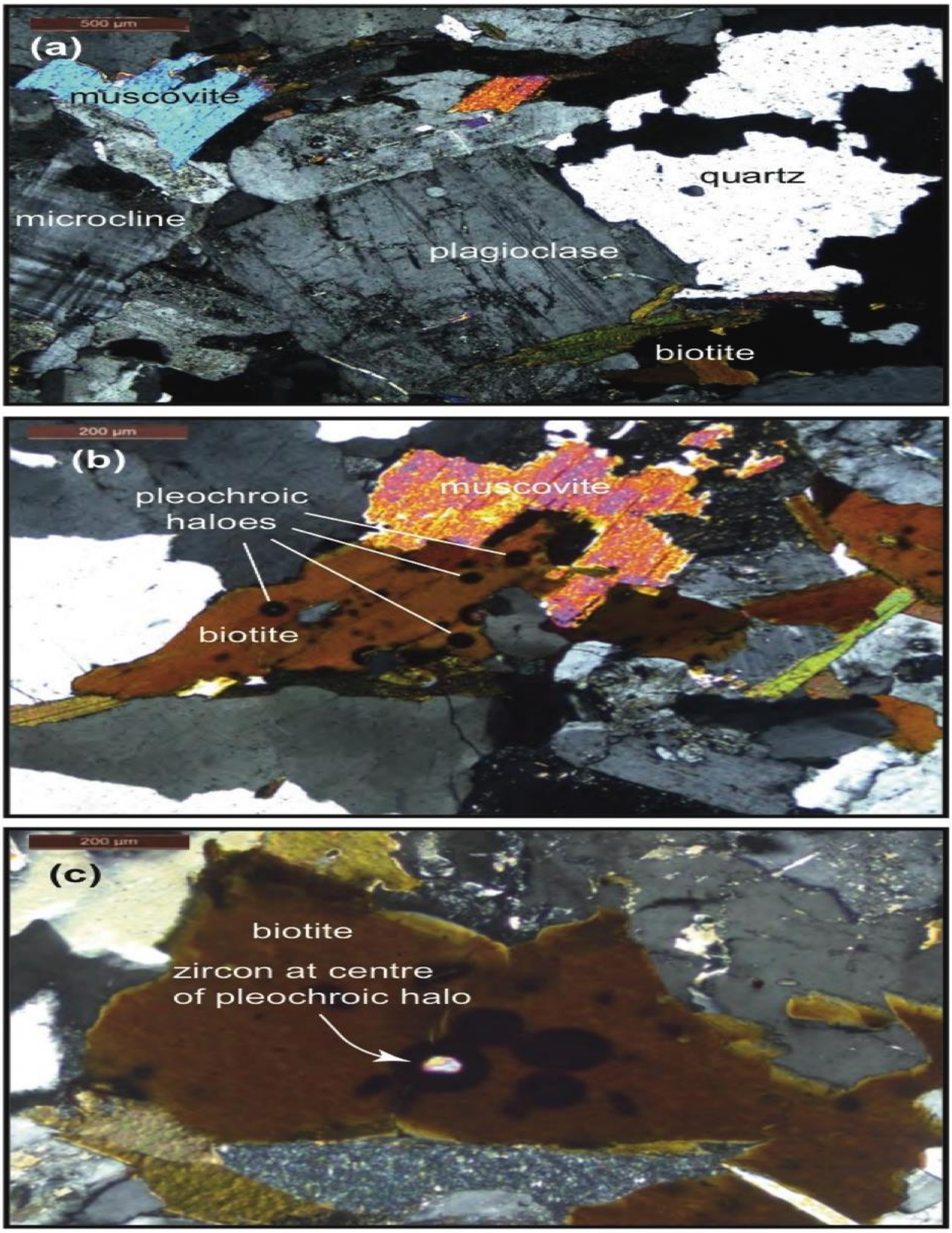

Figure 3 (a), (b), (c): Petrology of the Aberdeen Granite Pluton

Accessory minerals are important in the context of the geothermal potential of this pluton as they are the principal repositories of uranium and thorium that undergo radioactive decay and generate heat as a by-product. A very early study recognised that monazite, a thorium-bearing cerium phosphate, is more abundant than zircon in the Rubislaw quarry outcrop, zircon being an uranium-bearing zirconium silicate (Mackie, 1926[25]). Accessory phases are often trapped within biotite crystals that accumulate the damage from alpha-particle emissions in the form of dark haloes around microscopic inclusions. Both zircons and monazites display this effect and Figure 3c shows a highly birefringent zircon enclosed within a dark halo trapped in a brown biotite crystal among many other similar haloes. **The abundance of these radiation-generated haloes in the Aberdeen granite is at least as great as in any other major granite pluton in Scotland.**

WHOLE ROCK GEOCHEMISTRY

The weathered and fractured material in the surrounding area and from the on-site shallow boreholes is unsuitable for petrological and geochemical investigations. Consequently, fresh granite samples from surrounding quarries are used. Four samples were obtained from the Dancingcairns and four samples from the Dyce quarries some 2.4km SE and 3.7km NNW of the Rowett site respectively. Six further samples were taken from the best known location of the Aberdeen granite at the abandoned Rubislaw quarries located 5.8km to the SSE. Examination of these 14 samples taken from a wide area of the pluton confirms their broad similarity and supports their use as unaltered representatives of the granite body underlying the Rowett site.

DEEP TEMPERATURE PROFILE

An important factor in determining the target depth of the single well to be drilled at the AECC site is the expected temperature of the rock and fluid. As with all geothermal projects, the temperature cannot be known for certain until drilling to the target depth has been completed. Without sub-surface data, the only way to estimate the temperature is to model the change in temperature from surface to target depth using thermal modelling methods based on measurements and estimates of the major parameters that influence temperature.

Following the energy crisis of the 1970s, a detailed evaluation of the UK's geothermal potential was undertaken and some deep sources of heat in granite bodies were identified, including a number of granites in NE Scotland exemplified by the Cairngorm granite (Downing & Gray, 1986). Four boreholes were drilled into granites at Cairngorm, Ballater, Bennachie and Mount Battock to depths of approximately 300m and data obtained from cores and surface outcrops were combined with data from the literature to form the basis of one-dimensional geothermal modelling studies (Lee, 1986[26], Wheildon & Rollin, 1986[27]). The modelling approach used in these reports is adopted in this study with the *important difference of taking into account glacial cooling effects on estimates of temperature at depth*. As the results of thermal modelling are very dependent on the values given to various parameters, the reasons for the values chosen is reviewed in the sections below.

SURFACE HEAT FLOW (Q_0)

Surface heat flow is estimated from the thermal gradient and thermal conductivity obtained from boreholes. In the case of NE Scotland, these boreholes are all shallow (≤300m) and subject to thermal perturbations due

[25] Mackie, W. (1926). The heavier accessory minerals in the granites of Scotland. *Transactions of the Edinburgh Geolocial Society* **12**, 22-40.
[26] Lee, M. K. (1986). Heat flow. In: Downing, R. A. & Gray, D. A. (eds.) *Hot Dry Rock*: British Geological Survey, 21-41.
[27] 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, 8-20.

to the last ice sheet. No direct estimate of q_0 is available for the granite area of Aberdeen, although q_0 in Moine and Dalradian rocks hosting the granite are estimated to range from 40 to 55 mWm^{-2} (Lee, 1986). A large swathe of granites stretching from near Aberdeen to Cairngorm has much higher heat flow with q_0 often exceeding 70 mWm^{-2} (Lee, 1986) while a very low value of 29 mWm^{-2} was obtained at Tilleydesk (Ellon) about 25 km north of the AECC site (Burley *et al.*, 1984[28]). A review of the heat flow data for Scotland as a whole concluded that the Tilleydesk estimate was unreliable and a mean value for Scotland of 57 mWm^{-2} was derived using only data considered reliable (Gillespie *et al.*, 2013[29]). Based on this range of data a value of 50 mWm^{-2} is chosen here to represent the apparent surface heat flow q_0 in the Aberdeen granite.

It has long been accepted that predicting temperatures at depth using surface heat flow is unreliable in regions affected by relatively recent glaciation. Thermal measurements in shallow boreholes may not yet have reached a steady state leading to anomalously low thermal gradients and thus anomalously low estimates of heat flow (Beardsmore & Cull, 2001[30]). In the 1986 review of geothermal potential in the UK, q_0 was thought to have been underestimated in E Scotland by about 5-10 mWm^{-2} (a value of 7.5 is used for this modelling) whereas a more recent European-wide study calculated the deficit in q_0 at Aberdeen (as interpolated from their maps) to be about 15 mWm^{-2} (Majorowicz & Wybraniec, 2011[31]). More recent modelling for the UK puts the estimate for NE Scotland at 18 mWm^{-2} (Westaway & Younger, 2013[32]). Palaeoclimate corrections for individual plutons in the East Grampians have recently been estimated with ranges form 16.8 to 21.7 mWm^{-2} with a mean value of 19.3 mWm^{-2} (Busby *et al.*, 2015[33]). In selecting the most appropriate figure for the deficit in q_0 it should be noted that Aberdeen was located very close to the ice front for around 5,000 years until about 15,000 years before present as the British-Irish Ice Sheet retreated (Clark *et al.*, 2012[34]). Locations just in front of major ice sheets tend to suffer deep chilling and permafrost due to katabatic winds (extremely cold dense volumes of air descending from the ice caps), whereas locations under the ice sheet are relatively insulated from these effects. There is abundant evidence of deeply frozen ground in the area of interest around Aberdeen in ice wedge structures that form when soil contracts and cracks at temperatures below -15 to -20°C, although their age is not yet well constrained (Gemmell & Ralston, 1984[35]). Given the range of suggested corrections and their large effect on the predicted temperature the full range of climatic correction estimates is included in the modelling.

HEAT PRODUCTION (A)

The presence of radioactive elements, principally uranium, thorium and potassium, in rocks such as granites, leads through radioactive decay to the accumulation of heat energy over time. Heat production in surface rocks (A_0) can be estimated using empirical formulae based on gamma ray activity or the concentrations of the principal radioactive elements (K, U and Th) present in the rock and its density (Rybach, 1988[36]). No published

[28] Burley, A. J., Edmunds, W. M., Gale, I. N. (1984). Catalogue of geothermal data for the land area of the United Kingdom. Second revision April 1984. *Investigation of the Geothermal Potential of the UK*: British Geological Survey.
[29] Gillespie, M. R., Crane, E. J., Barron, E. J. (2013). Deep geothermal energy potential in Scotland. *British Geological Survey Commissioned Report*, 129pp.
[30] Beardsmore, G. R. & Cull, J. P. (2001). *Crustal Heat Flow*. Cambridge: Cambridge University.
[31] Majorowicz, J. & Wybraniec, S. (2011). New terrestrial heat flow map of Europe after regional paleoclimatic correction application. *Int J Earth Sci (Geol Rundsch)* **100**, 881-887.
[32] Westaway, R. & Younger, P. L. (2013). Accounting for palaeoclimate and topography: A rigorous approach to correction of the British geothermal dataset. *Geothermics* **48**, 31-51.
[33] Busby, J., Gillespie, M., Kender, S. (2015). How hot are the Cairngorms? *Scottish Journal of Geology* **51**, 105-115.
[34] Clark, C. D., Hughes, A. L. C., Greenwood, S. L., Jordan, C., Sejrup, H. P. (2012). Pattern and timing of retreat of the last British-Irish Ice Sheet. *Quaternary Science Reviews*, 112-146.
[35] Gemmell, A. M. D. & Ralston, I. B. M. (1984). Some recent discoveries of ice-wedge cast networks in northeast Scotland. *Scottish Journal of Geology* **20**, 115-118.
[36] 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, 125-142.

data was found for gamma ray activity in the Aberdeen granite so heat production has been calculated for nine samples obtained from quarries as part of this study. K, U and Th were analysed by ICPMS on solutions prepared from rock powders fused in a flux of 80% lithium metaborate and 20% lithium tetraborate dissolved in nitric acid. Density was estimated from the mass of the sample and the mass of sample suspended in pure water. The K, U, Th and density data and the heat production values obtained using the Rybach formula are presented in Table 3. Although the variability in model heat production is quite large in these samples the mean value of 2.0 μWm^{-3} is close to the mean value of 2.1 μWm^{-3} calculated from three samples of the Aberdeen granite published in a thesis on UK granites (O'Brien, 1985[37]) and is closely comparable with a mean value from three samples of 2.2 μWm^{-3} quoted in the 1986 UK geothermal review (Lee, 1986). A mean value of 2.1 μWm^{-3} is used for A_0 in the present modelling.

SURFACE THERMAL CONDUCTIVITY (Λ_0)

Four outcrop samples were collected from the Aberdeen granite and thermal conductivity was measured in the laboratory using portable divided bar apparatus at St Andrews University specifically designed for measuring thermal conductivity in rock samples (Antriasian, 2010[38]). Samples were cut into cubes or cuboids with a diameter of up to 65mm and no thicker than 13mm. The two faces were polished to achieve parallel surfaces for maximum contact with thermal plates. Three to seven measurements were made per sample and the summary results are presented in Table 3. The best estimate for λ_0 from these samples is 2.71 $Wm^{-1}K^{-1}$ +/- 0.28 (1σ). The BGS GeoReport[39] for the area provides a value for thermal conductivity of 3.27 $Wm^{-1}K^{-1}$, although it is not clear how this value was determined and whether it was obtained from local granite samples or derived from regional data (BGS, 2015). Given that the BGS GeoReport is mostly computer generated from generic data, the 2.71 $Wm^{-1}K^{-1}$ value obtained from laboratory testing of samples from known locations is used for λ_0 in the modelling.

A THERMAL MODEL FOR THE AECC DGSW SITE

This section deals with the use of thermal modelling to predict the temperature of rocks that will be encountered at depth. As there are no deep wells in this vicinity and detailed land-based deep geophysical surveys are lacking, the modelling is not ideally constrained, consequently a range of outcomes is possible. One-dimensional heat flow modelling has been undertaken (Figure 4); **with no deep drilling or deep geophysical datasets available onshore in Scotland it is considered that there is very limited value in performing two or three dimensional modelling.** Any modelling of this type performed without site based deep data should be considered with caution. Every effort has been made to identify the most appropriate model parameters whilst recognizing that improved accuracy of temperature prediction will only come from deep drilling in the area; as highlighted above, the same will apply to all other deep geothermal prospects in Scotland.

The model assumes that the single vertical well will remain in similar granite throughout and thus a constant vertical distribution of heat production may be appropriate. An alternative model that assumes an

[37] O'Brien, C. (1985). The pretrogenesis and geochemistry of the British Caledonian granites with special reference to mineralized intrusions (PhD thesis). *Geology*: University of Leicester.
[38] Antriasian, A. M. (2010). The Portable Electronic Divided Bar (PEDB): a Tool for Measuring Thermal Conductivity of Rock Samples. *Proceedings of the World Geothermal Congress*. Bali, Indonesia, 7pp.
[39] BGS. (2015). GeoReport GR_212158/1. British Geological Survey, 14pp.

exponential distribution of heat production with depth yields a temperature profile that differs by less than 1°C over the interval of interest and is not developed further here. The average ground temperature is assumed to be 9.2 °C (BGS, 2015).

The aim of the single well project is to achieve a fluid temperature at the bottom of the borehole of 60-65°C at depths of between 2.0 and 2.25 km. The modelling identifies that this is a realistic expectation if the conservative assumptions (based on measured parameters and the most recent literature values) hold to be correct to the target depth.

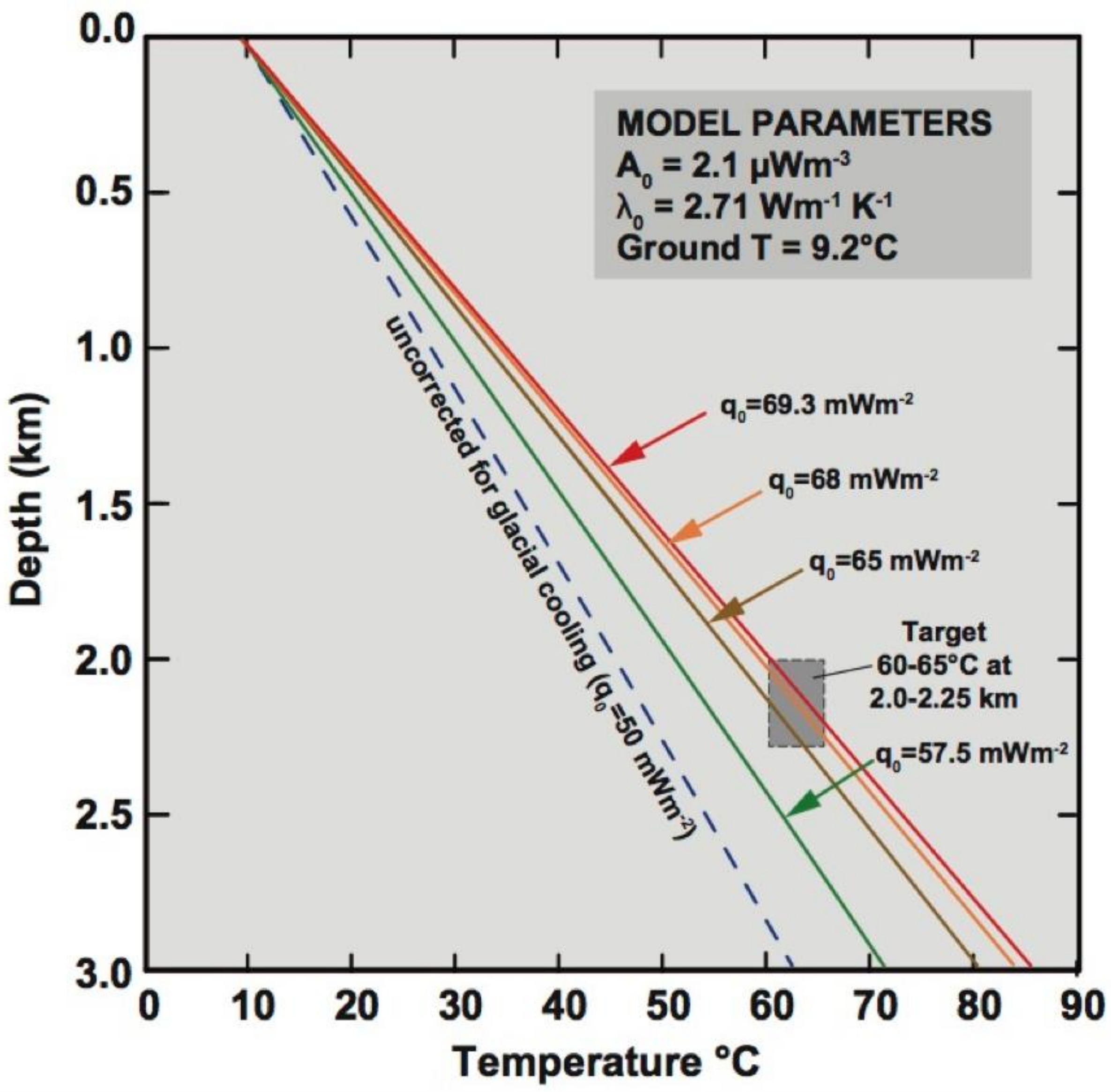

Figure 4 Steady state temperature profiles with depth at the new AECC site near Aberdeen based on a standard heat flow model (Wheildon & Rollin, 1986) and assumptions discussed in the text. Solid lines represent q0 values corrected for palaeoclimate according to different estimates (see text for explanation) whereas the broken line represents q0 before applying a correction.

SAMPLE	LOCALITY	GRID REFERENCE	ROCK TYPE	DENSITY			THERMAL CONDUCTIVITY			HEAT PRDUCTION			
				kgm^{-3}	s.d.	N	$Wm^{-1}K^{-1}$	s.d.	N	K %	Th ppm	U ppm	A0 μWm^{-3}
82AB23	Rubislaw quarry	NJ39128054	Bi musc granite	2678*			n.d.			3.35	18.12	2.35	2.15
82AB24	Rubislaw quarry	NJ39128054	Bi musc granite	2678*			n.d.			3.47	12.63	3.97	2.20
82AB29	Dancingcairns quarry	NJ39048090	Bi musc granite	2678*			n.d.			3.43	15.32	1.53	1.76
82AB30	Dancingcairns quarry	NJ39048090	Bi musc granite	2678*			n.d.			3.60	25.83	2.35	2.70
82AB34	Dyce quarry	NJ38668137	Bi musc granite	2688**			n.d.			3.27	15.14	2.11	1.88
19a	Dyce quarry	NJ38668136	Bi musc granite	2688	7	4	2.80	0.16	2	3.51	24.88	1.72	2.48
19b	Dyce quarry	NJ38668136	Bi musc granite	2676	7	4	2.63	0.17	6	3.37	12.32	2.03	1.67
19c	Perseley quarry	NJ39038104	Bi musc granite	2675	10	4	2.60	0.37	6	3.33	10.89	2.32	1.65
19d	Perseley quarry	NJ39038104	Bi musc granite	2673	1	4	2.79	0.26	3	3.43	11.70	1.53	1.51

Table 3. New determinations of heat production (A0) and thermal conductivity (λ0) and density for the Aberdeen granite with their locations. See text for methods used.

British Geological Survey Ground Source Heat Pump (GSHP) Geo Report

A ground source heat pump report was obtained from the British Geological Survey (BGS) to provide an estimate of mean annual ground temperatures at the site.

The BGS report provides an estimate of temperatures at depths of between 1m and 200m below the ground surface that "*are made from an estimate of the local heat flow and the thermal conductivity of the bedrock geology*". The report estimates the thermal conductivity ($W\ m^{-1}\ K^{-1}$) of the granite bedrock to be $3.27W\ m^{-1}\ K^{-1}$ and the thermal diffusivity to be $0.1284\ m^{2}\ day^{-1}$ with an estimated temperature at 200mbgl of $13^{o}C$.

The report states that temperatures at a depth of below 15m are "*affected by the small amount of heat conducted upwards from the sub-surface*" which in the UK "*creates an increase of temperature with depth that has an average value of 2.6^{o}C per 100m*". Based on this average temperature gradient the average temperature at 2000mbgl would be estimated at $60^{o}C$ and $73^{o}C$ at a depth of 2500mbgl which are within the ranges identified by the thermal modelling exercise undertaken for the site.

GEOCHEMISTRY OF THE SITE

GENERAL SETTING

This section addresses the composition of fluids and gases that originate in deep rocks and could be channeled to the surface by the proposed DGSW with contaminating effects on the surface environment in ways potentially deleterious to ecologies and human activity. The geochemistry will also influence the choice of materials used in the heat exchanger selected for the site. For this reason it is important to assess the likely impact in advance of drilling.

The composition of surface waters is well documented but the nature of waters from depths that the DGSW will encounter at the Rowett site (approximately 2 km) may have very different origins and be quite different in composition. Addressing this issue directly is currently not possible without access to boreholes of similar depth but analogous geological settings have been investigated worldwide and general patterns emerge that can be applied to the geology of the Aberdeen granite. Another aspect of deep drilling in granite addressed in this section is the possibility of radon escaping to the surface, especially given the hazardous levels of radon detected in many dwellings to the west of the proposed site.

SITE SPECIFIC GEOCHEMISTRY (INCLUDING AT 2KM DEPTH)

The sources of surface waters and groundwaters at the site and the vulnerability of the groundwater aquifers to contamination have been discussed in an earlier section. These are important for agriculture as well as domestic use, public water supply (including recreation such as golf course) and the food and drink industry (including whisky). All the water in the area is young with no evidence of palaeowater and any contamination by deep waters from the DGSW is likely to introduce older waters of a very different composition. A baseline for groundwater composition is provided by recent studies of Scotland and Aberdeenshire in particular[40,41]. While these reports provide useful general ranges of the main compositional parameters none provides specific information on the composition of groundwaters hosted by the Aberdeen granite or its close analogue, the Kemnay granite.

Literature describing the composition of water in rocks at depths similar to the planned DGSW (approximately 2km) generally identify three components that may contribute in greater of lesser proportions, namely:

a) surface water from various forms of precipitation
b) a seawater component derived from modern or fossil seawater
c) the products of chemical reactions between water and the rocks at depth where increased temperature and long periods of time may have a major effect on water chemistry.

The possibility of seawater is included here as the eastern margin of the Aberdeen granite lies very close to the coast but as no evidence of substantial amounts of seawater was found in any of the shallow aquifers of Aberdeenshire, a major marine influence is not likely to be present at 2 km depth.

Granite at depths of 2km would normally have some degree of interconnected fracture porosity enabling some hydraulic conductivity to form. The fluids trapped in the fracture pore system are usually highly mineralised salt-rich water or brines that can react with constituents of the host rocks. The Aberdeen granite consists predominantly of the primary minerals plagioclase, alkali feldspar (orthoclase and microcline), quartz, biotite and muscovite along with minor iron and titanium oxides, zircon and the phosphate minerals apatite and monazite. Alteration of these minerals by geothermal waters at temperatures expected at the base of the DGSW (60-70°C) is likely to lead to new minerals including the clay minerals kaolinite and montmorillonite, the zeolite laumontite and amorphous analogues of gibbsite. The solution tends to increase in total dissolved solids with depth and at 2km depth may amount to a few hundred gL^{-1}.

Very few studies exist on the chemical nature of geothermal fluids in bodies of granite at broadly similar depths and temperature ranges to the proposed DGSW at the AECC. Those that are available, discussed in the next paragraph, are important as they might are provide some guidance on the nature of contaminants that could reach the surface during the operation of the well.

The Rosemanowes borehole at Carnmenellis, Cornwall is sited in a granite that is petrologically quite similar to the muscovite biotite granite of Aberdeen. Extensive research was carried out on ground waters at the surface, in mines and in boreholes during the hot dry rock project in Cornwall[40]. The composition of the waters reflect a mixing between surface meteoric waters and deeper brines, the latter being the products of water rock interaction over long time periods[41]. Thermal groundwaters of over 50°C are observed in old tin mines and are generally saline, probably resulting from alteration reactions with biotite and plagioclase. An unusual feature is the high concentration of Li and sometimes Rb, Cs and F in the groundwaters which reflects a geochemical characteristic of the Cornish granites, a feature that is unlikely to be as pronounced in the Aberdeen granite. Groundwater salinities can reach up to 300 gL^{-1} but this high salinity is not considered to be an indicator of a major seawater source. An experimental replication of the Carnmenellis geothermal system involved reacting drill core samples taken from a 2km in the granite with Na-HCO_3-Cl fluids at temperatures of 80°C and above at pressures of 50 MPa for up to 200 days[42]. The dissolution of plagioclase and formation of smectite and calcite was the principal observed effect of water-rock interaction in these experiments.

[40] Smedley, P.L., et al., *Geochemistry in relation to Hot Dry Rock development in Cornwall. Volume 4. Fluid circulation in the Carnmenellis granite: hydrogeological, hydrogeochemical and palaeofluid evidence*, in *British Geological Survey Research Report*. 1989: Keyworth, Nottingham.

[41] Edmunds, W.M., et al., *The evolution of saline and thermal groundwaters in the Carnmenellis granite.* Mineralogical Magazine, 1984. **48**: p. 407-424.

[42] Savage, D., et al., *Hydrothermal alteration of granite by meteoric fluid: an example from the Carnmenellis Granite, United Kingdom.* Contributions to Mineralogy and Petrology, 1987. **96**: p. 391-405.

Another example can be found in California where two wells at Cajon Pass were sampled over uncased intervals at around 2km in order to extract fluids from fractures within granitic rocks[43]. Major differences were observed between the fluids recovered from different fracture systems. Salinity varied from 0.95 to 2.15 gL^{-1}, very low compared with Carnmenellis, and there were very large variations in Cl, Ca, Na, Fe, HCO_3 and SO_4. This study demonstrates that water composition may vary significantly if they have become isolated after following different evolutionary paths.

Geothermal fluids in the shield areas of North America tend to have very high salinities, exceeding 300 gL^{-1}. These brines are also acidic in terms of pH. As with Carnmenellis, the origin of these brines is not considered to be sea water but due rather to reactions between rather dilute aqueous solutions (i.e. waters with low total dissolved solids) and the primary minerals of a largely granitic upper continental crust. The products of these reactions include new minerals such as zeolites, clays and quartz along with an aqueous fluid carrying a high burden of total dissolved solids.

POTENTIAL FOR SURFACE WATER POLLUTION

The analogue studies above indicate a significant degree of variation in the fluids associated with granite hosted geothermal systems. Significant variability is found in salinities, total dissolved solids and pH as well as the major cations and anions which determine the contaminants that can be transported to the surface. The closest analogue to the Aberdeen granite is Carnmenellis, which demonstrates the importance of the chemistry of the host rock in determining the composition of the fluids. As the Aberdeen granite is rather deficient in heavy metals it is very unlikely that any fluids from the DGSW will be the cause of significant environmental contamination by heavy metals.

Other possible contaminants for which special handling may be necessary include the halogens although it is unlikely that any recovered brines will be as saline as sea water. There also is a possibility that lithium (probably largely derived from the alteration of micas) will be present in the fluids and some geothermal plants are considering turning this into an asset by recovering and selling lithium although it is very unlikely to be an economic prospect at the proposed site.

The principles of water-rock interaction are now well understood and amenable to modelling. When rocks and fluids are recovered from drilling to depth at the Rowett site it will be possible to model the system and make better predictions concerning the composition of fluids.

RADON GAS

The granites of the eastern Grampian Highlands are known for high levels of radon. Radon has been implicated as a significant cause of lung cancer in non smokers and a recent Scotland-wide study measured the distribution of the radioactive gas in homes. Figure 5 shows the distribution of homes that exceed the action Level of 200 Bq m^{-3} by 30% or more (deepest brown ornament) over the main area of granites in the eastern Grampians[44]. Using this measure of radon emissions it is clear that the Aberdeen granite underlies an area of very low radon emission. This is related to rather low levels of uranium in the bedrock granite compared with the biotite granites further to the west including those at Banchory [45]. An earlier smaller scale study of radon

[43] Kharaka, Y.K., et al., *Geochemistry of water at Cajon Pass, California: Preliminary results.* Geophysical Research Letters, 1988. **15**(9): p. 1037-1040.

[44] Miles, J.H.C., et al., *Indicative Atlas of Radon in Scotland*. 2011, Health Protection Agency and British Geological Survey. p. 27pp.

[45] Scheib, C., et al., *Geological controls on radon potential in Scotland.* Scottish Journal of Geology, 2009. **45**(2): p. 147-160.

dissolved in water supplies from wells in the Aberdeen area found that this source makes only a small contribution to radon levels[46].

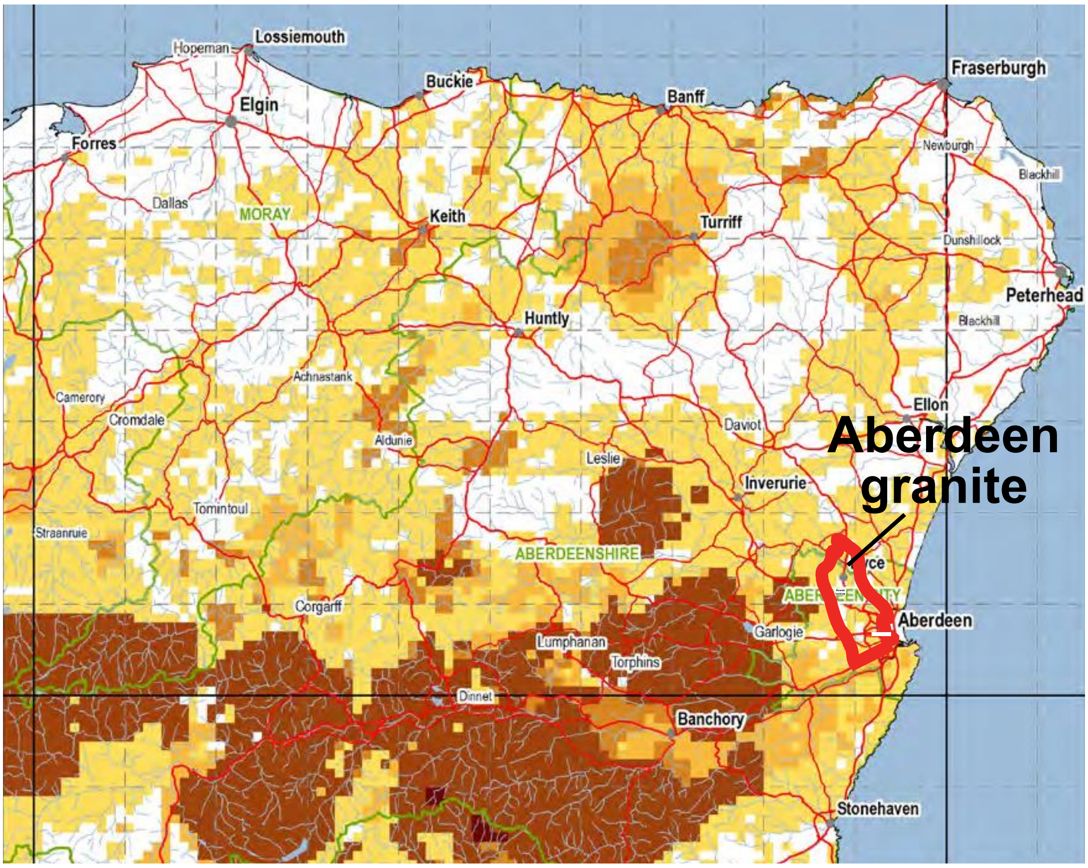

Figure 5 Radon level as indicated by levels of the radioactive gas measured in dwellings. Deep brown pixels represent the highest levels. Note the near absence of radon in dwellings over the area of the Aberdeen granite (delineated by a red line). Map taken from the report of Miles et al. (2011).

SUMMARY

A review of the literature on the geochemistry of natural materials at the surface in the vicinity of the proposed DGSW in Aberdeen and on analogous geothermal wells elsewhere in the UK and beyond leads to the provisional conclusion that there is a very low probability of significant sources of pollution in fluid and gaseous form contaminating the site and its surrounds from the drilling and production of deep geothermal heat from a DGSW at the AECC site.

[46] Al-Doorie, F.N., B. Heaton, and C.J. MArtin, *A study of the 222Rn in well water supplies in the area of Aberdeen, Scotland.* Journal of Environmental Radioactivity, 1993. **18**: p. 163-173.

REVIEW OF AECC SITE

EXISTING SITE

The site, currently known as the Rowett, Aberdeen, is located at National Grid Reference NJ 884 105. The area is of an irregular shape with approximate maximum dimensions of 1.1km (east-west) and 0.9km (north-south) as shown in Figure 6. The area of the site is approximately 60 hectares.

PROPOSED DEVELOPMENT

The Proposed AECC Development will include the construction of the new Aberdeen Exhibition & Conference Centre (AECC) that incorporates a new arena and conference centre structure (Fig 7). In addition, the development includes a subterranean car park, associated roads and over ground car parks and areas of soft landscaping.

The development will incorporate a range of renewable energy technologies including hydrogen cell and anaerobic digestion and it is considered that deep geothermal heat could provide a significant contribution to the to the mix of energies being demonstrated at the site and also provide heat to nearby dwellings that will be most affected by the development. It is also expected that a number of additional buildings including offices and hotels will be developed at later stages of the project. The site is located just to the South of Aberdeen Airport.

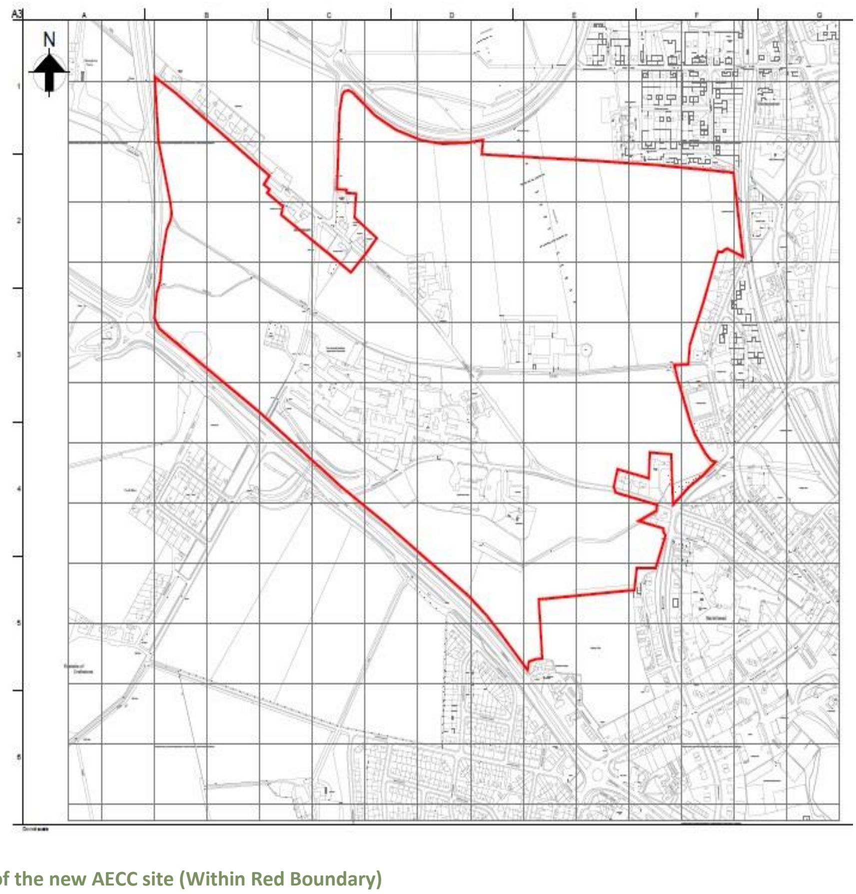

Figure 6 Location of the new AECC site (Within Red Boundary)

Figure 7 Proposed design for the AECC Centre

OUTLINE WELL DESIGN

The DGSW technology consists of a single, vertical well drilled to a nominal depth of 2km. The actual depth of the well is determined by the required delivery temperature to the building or plant and the natural temperature gradient at the site. In most locations in the United Kingdom, the temperature at a depth of 2km is sufficient to provide a delivery temperature adequate for space heating purposes. The well is steel cased (using standard oil and gas casing diameters) to within 300m of the base of the well. The remainder of the well is either open hole (i.e. exposed to the surrounding rock) or cased with perforated casing. The well at AECC will be open hole at the base due to the anticipated competency of the granite. A polypropylene pipe is then installed to within 50m of the bottom of the well and a submersible pump installed to a depth of circa 200m within the polypropylene pipe. Water is drawn up through the pipe that also acts as an insulator. This heated water is then passed through a heat exchanger, the thermal energy removed, and the cooler water rejected back to the top of the well. As the depth of the well governs the delivery temperature (and is well constrained), the system can be designed to suit the flow and return temperature of the building. Depending on the type of end use, delivery temperatures will be between 45 and 75°C. A low temperature requirement is cheaper to deliver as the well can be drilled to a shallower depth. A schematic design of the system is shown in Figure 8.

The DGSW has been designed to use off-the-shelf materials and to be easy to install (install time of two weeks post-drilling) and maintain. The design has been extensively modelled, both analytically and numerically as part of a previous DECC funded project. The results show that the system can achieve peak thermal delivery rates of between 400 and 600kW and supply between 2 and 3.5GWh of heat per year depending on the building utlisation rate. The system has also been field testing in an existing well in 2014 as part of a previous DECC funded project. The trial showed that **for every one unit of electricity used by the pump, between 40 and 50 units of thermal energy can be delivered at the surface**.

The level of modelling and testing performed on the DGSW is considered to place the system at a technology readiness level (TRL) of TRL 6 where a "*system has been installed and tested in a relevant environment"*. Through developing the technology to this level, the DGSW system is at the point where it can be incorporated into a commercial project.

The well construction and drilling methodology used by Geothermal Engineering Ltd has been approved by the on shore Health and Safety Executive for a recent project at the Crewe Campus of the Manchester Metropolitan University. The design and methodology was also approved by the Environment Agency in England who gave permission to drill a proposed 2km vertical well at the Crewe Campus. This design would be very similar to that proposed at the AECC site.

The major components of the system are:

Component	Purpose
Polypropylene Pipe	Insulate the hot water as it is drawn from the bottom of the well to the surface
Submersible Pump	Draw water from the bottom of the well to the top
Flexible Riser	Transport water from the submersible pump to the surface
Thermistor string	Monitor temperature in the well during operation
Surface pipework	Connections between the well and the plant room
Steel weights	Fitted to the polypropylene pipe to avoid negative buoyancy
Cable ties and sundries	Attach the thermistor string to the polypropylene pipe
Connection pipework	Pipework interface at the wellhead
Bleed valve and isolation valves	Bleed flow control during peak delivery periods
Temp and flow sensors/ meters	Monitoring equipment to calculate heat delivery
Pump control system	Control apparatus for the submersible pump
Insulation	Pipework insulation in the plant room
Fittings	Pipework connections within the plant room
Heat exchanger	Point of delivery of heat from the DGSW to the existing network
Filtration unit	Cyclonic filter to remove any particulates prior to the DGSW water entering the heat exchanger

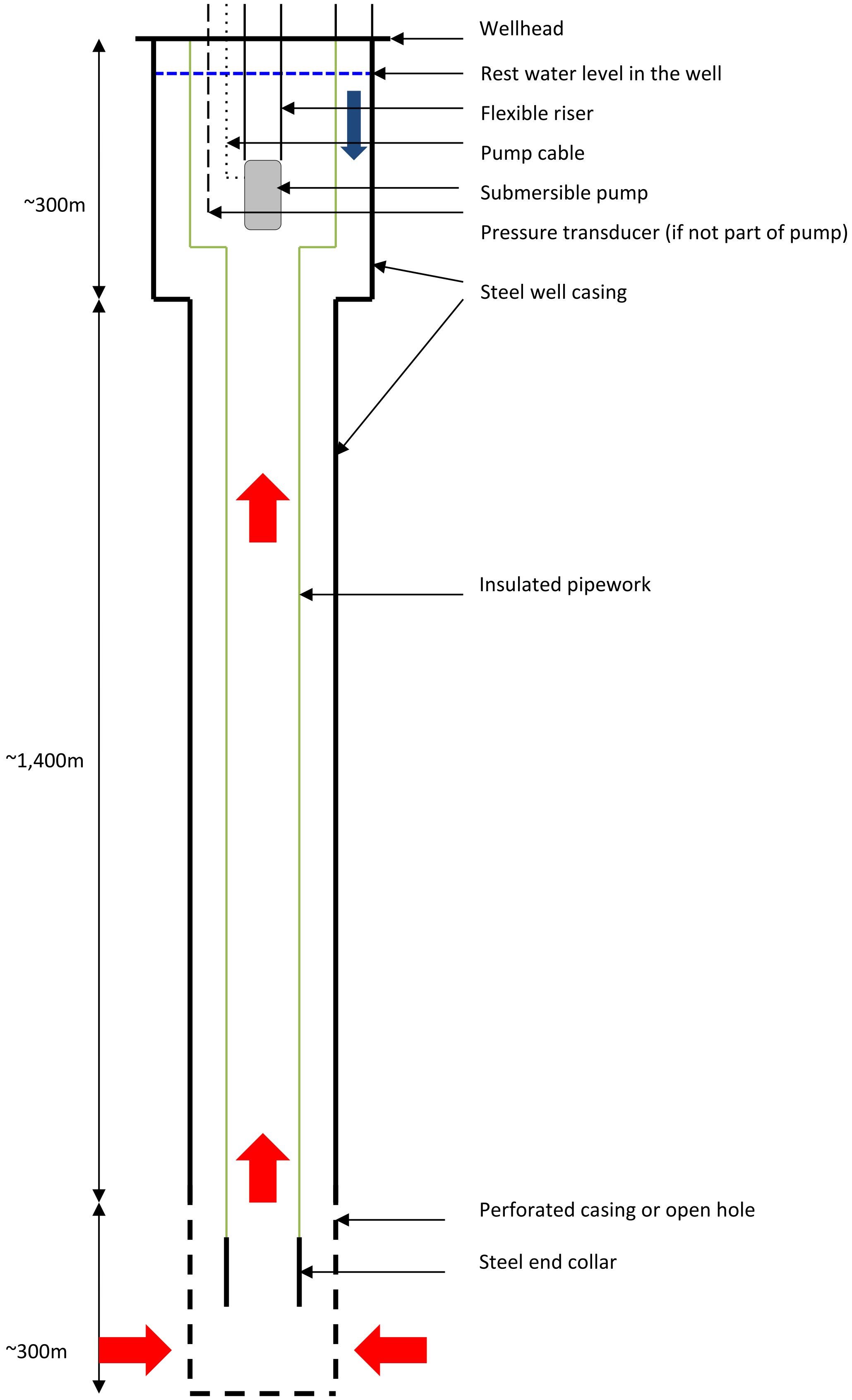

Figure 8 Schematic of the proposed well for the AECC site

OPERATIONAL MODES

The system has been designed to operate in two principal modes (Figure 9):

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

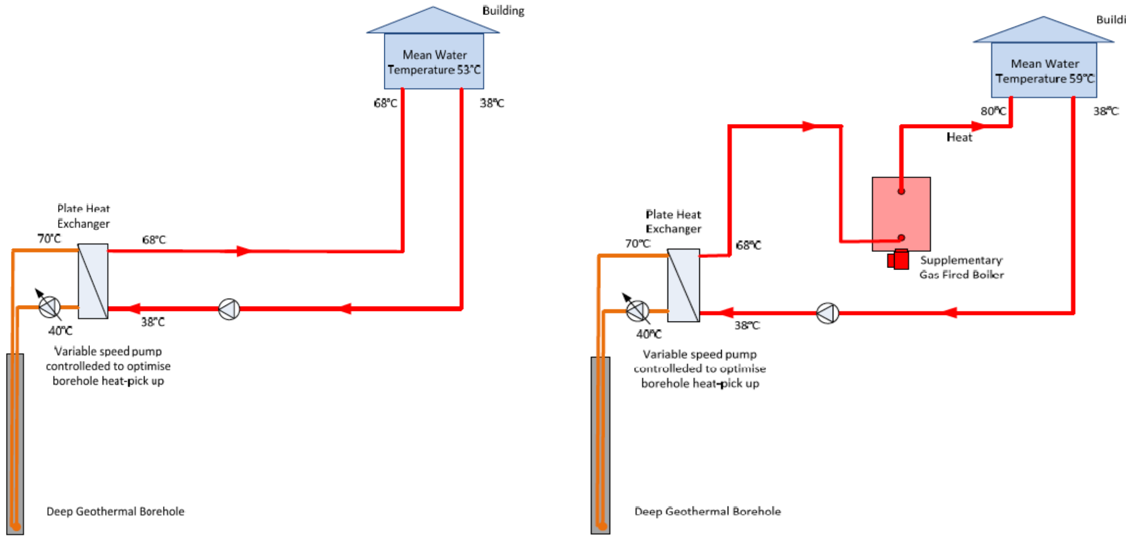

Figure 9 DGSW in monovalent and bivalent mode

In a standard heat supply project, to maximise the thermal output of the DGSW, the operation of existing heating systems will be adapted to run on a lower mean water temperature (MWT) than the norm (Figure 9). 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. Thermal storage will also be added to the system (if not already in place) to provide better regulation of the delivery temperature.

In monovalent form, the system provides a simple robust solution to the delivery of heat with very low carbon content to buildings with underfloor heating or lower temperature distribution systems. We would expect to deploy the monovalent system in all new builds. The bivalent system is likely to be the form most commonly implemented in early stage retrofit projects.

OPERATION

The operation of the system is managed through the control of the submersible pump flow rate and the bleed valve (Figure 10). The DGSW reaches peak delivery temperatures after approximately 35 minutes of operation and therefore the submersible pump control will be linked into the Building Management System (BMS) to trigger the pump to start prior to the heating being required in the buildings. For the AD unit at the AECC, the system will have little downtime and therefore, once operational, will continue to pump at a fixed flow rate determined by the AD heat demand. Depending on the seasonal requirements of the residential units, the flow rate may be increased in the winter periods. This will be determined once the well has been drilled and tested with the Thermal Response Test unit that was designed and constructed by GEL.

MAINTENANCE

The primary circuit (the DGSW system) will be circulating groundwater that may contain some dissolved solids, although the majority will remain at the bottom of the well. A cyclonic filtration unit will be installed on the primary circuit to prevent any remaining solids from passing through the heat exchanger (Figure 10).

The maintenance schedule will consist of monthly inspections of the filtration unit to ensure that there is no build up of sediments in the system. At the same time, water quality samples will be taken. During the monthly inspection, all aspects of the system will be checked for signs of deterioration or unexpected problems. On a yearly basis, the heat exchanger will be inspected and, if required, treated and cleaned. At the same time, the submersible pump will be removed from the well, inspected and cleaned if required. The pump removal and inspection will mean that the system is off-line for 6 hours.

INTERFACE WITH ANAEROBIC DIGESTION UNIT

The interface with the AD unit will be in the existing plant room and will consist of a 500kW heat exchanger with associated flow and return pipework. On one side of the heat exchanger is the fluid from the well, on the other, the fluid circulating within the AD unit. A schematic for a typical DGSW plant room is shown in Figure 10.

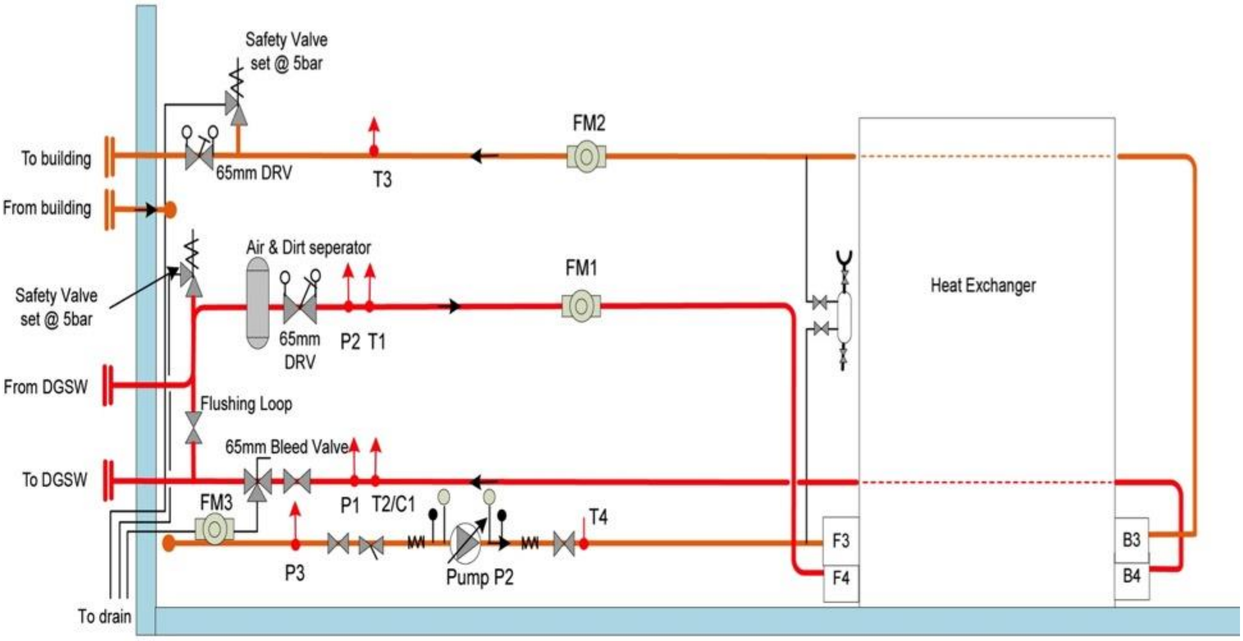

Figure 10 Plant room items and connection to the AD building

SOFT START AND SOFT STOP

The pump will be fitted with an inverter to achieve variable speed control. The pump will be soft-started with the speed ramped up over 2 minutes to overcome the inertia of the primary circuit water content and to establish sufficient motor cooling. This will avoid a low-pressure trip. Likewise, on shut down of the primary pump, a 'soft-stop' will be used to dissipate the momentum of the borehole circuit, ramping the pump speed down over 2 minutes.

INTEGRATION AND OPTIMISATION OF DGSW

The AECC site will showcase multiple renewable energy sources to supply the site with both heat and electricity. These sources will include an Anaerobic Digestion plant with a required heat input load of between 400 and 500kW for 24 hrs of the day, 365 days of the year. This heat load is particularly well suited to the delivery capacity of the deep geothermal single well. The AD plant is conceived as a gas to grid facility although there will also be a private pipe to provide a biomethane feed to the on-site CHP housed in the energy centre building. Whilst AD technology is well established in the UK at farm scale (operating on energy crops and farm residues) and as merchant bio-waste disposal facilities, there is less experience of operating AD plants as part of an integrated CHP facility. This is a particularly ambitious project integrating off-site fuel preparation and storage and on-site deep geothermal hot water supplies. The AD plant will comprise of an on-site component that includes: the reception building, the main AD digester and storage, gas-upgrade equipment and the gas injection point. At this stage it is anticipated that the AD facility will be a composite wet and dry AD plant (Figure 14). It is proposed that the plant will be sized to produce a biomethane stream for injection of just less than 40,000MWhrs annually together with a separate (unpropanated) bio-methane supply to the energy Centre of 16,500MWhrs. The planned annual output of the AD facility is 56,500MWhrs of biomethane.

The plant will be a co-digestion facility with agricultural and food waste substrates. The small dry digestion facility will be designed to take Aberdeen City garden waste collections (approx. 8500tpa) whilst the wet digestion will be fuelled with purchased agricultural crops and Aberdeen City food waste collections. Food waste collections are currently around 3500 tpa but these are expected to rise as the City undertakes nondomestic food waste collection services.

The usual approach for meeting the onsite energy demand for a biogas injection plant is to bleed off some of the generated biogas (before up grade) and run an onsite CHP unit to supply the parasitic loads. The intention is to replace this with the primary delivery from the DGSW (Figure 14).

Without the deep geothermal well the plant used will be:

- 500kWe CHP Unit (400kWth) high grade heat
- 600kWhth Biogas boiler

To fuel these units the generated biogas used will be approximately 1.7 million kWhrs. For the proposed AD plant the average parasitic electrical and thermal loads will be:

- Heat demand for the Wet AD tanks: approx. 200kW
- Heat demand for the Dry AD digesters: approx. 40kW
- Gas Upgrade (800kWth, 165kWe)
- AD plant 200kWe
- Pasteurisation Plant at 60C

If we assume that the DGSW is used to supply the low-grade heat then the 500kWe CHP unit can be eliminated saving approximately £500,000 of capital. A biogas boiler will still be required, however the operational savings could equate to around 1.9million kWhrs of biogas. If the gas is injected then the operational savings may be valued at (assuming 20% derogation on biomethane injection (4.5p RHI + 2.5p kWhr retail)) approximately £140,000 per annum.

The level of heat demand from the AD unit coupled to the capital and annual savings mean that this combination is a good match for the site and may be suitable to similar types of development in the future.

Further, the storage and delivery yard of the proposed AD unit has very good vehicular access for both drilling the well and for maintenance access during the lifetime operation (Figure 11). It is considered that this could be a unique demonstration of renewable technology providing direct heating to another renewable technology and could potentially be marketed as an alternative to CHP units that would be used to provide heat for the AD process. This demonstrates the versatility and commercial opportunity of the DGSW and its applicability to a wide range of heat end users.

It can also be seen from Figures 11 and 12 that there are a number of residential dwellings that are in close proximity to the AD unit. These units afford an excellent opportunity to use the return flow heat from the well to supply residential heat via a small scale heat network using high temperature Ground Source Heat Pumps in each dwelling to boost the delivery temperature (Figure 13). This combination of uses maximises the thermal output from the well and is a solution that we would look to employ on future projects. We also consider that this offers a major local community benefit to local people in close proximity to the site who could benefit from receiving sustainable low carbon geothermal heating. Therefore, there is the opportunity to showcase the provision of deep geothermal heat to two end users (commercial and domestic) from one DGSW. The opportunity to showcase two end-users for the DGSW heat means that the system can be successfully demonstrated to the widest possible number of potential investors.

Figure 11 Proposed location of the single well and associated pipework to supply heat to the AD unit and residential dwellings

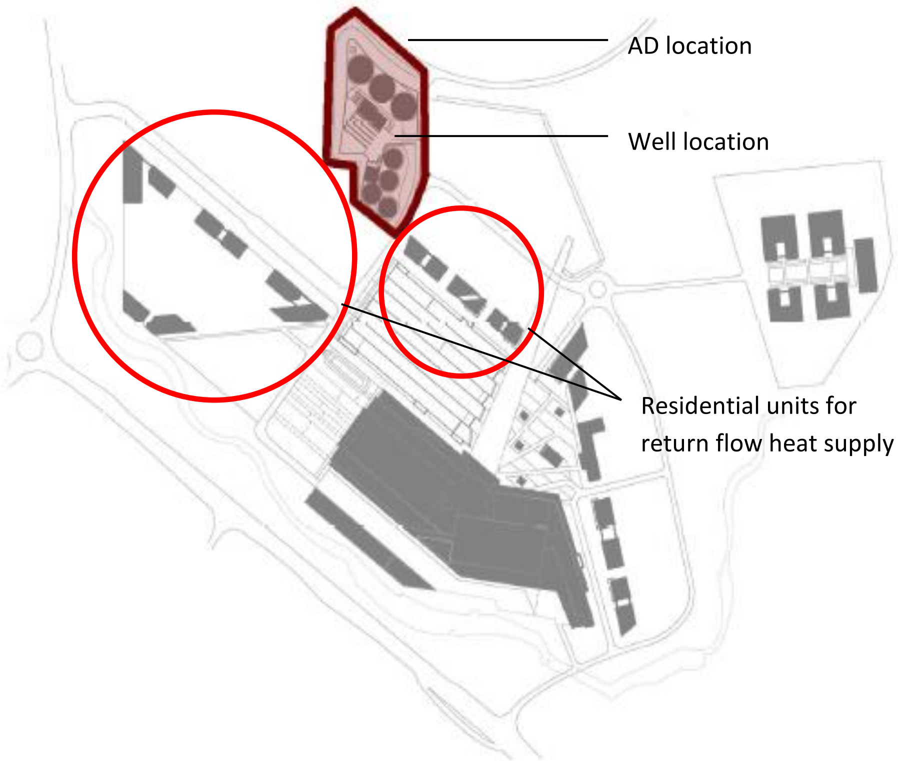

Figure 12 Location of AD unit, well and residential dwellings

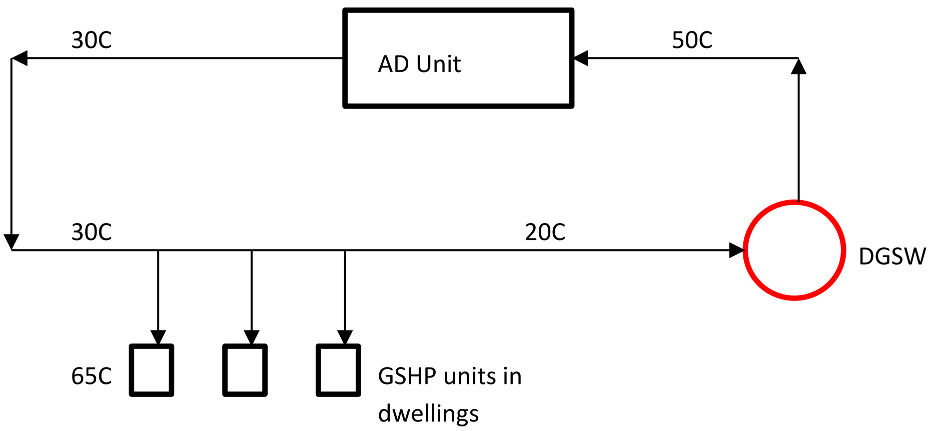

Figure 13 Schematic of the DGSW network

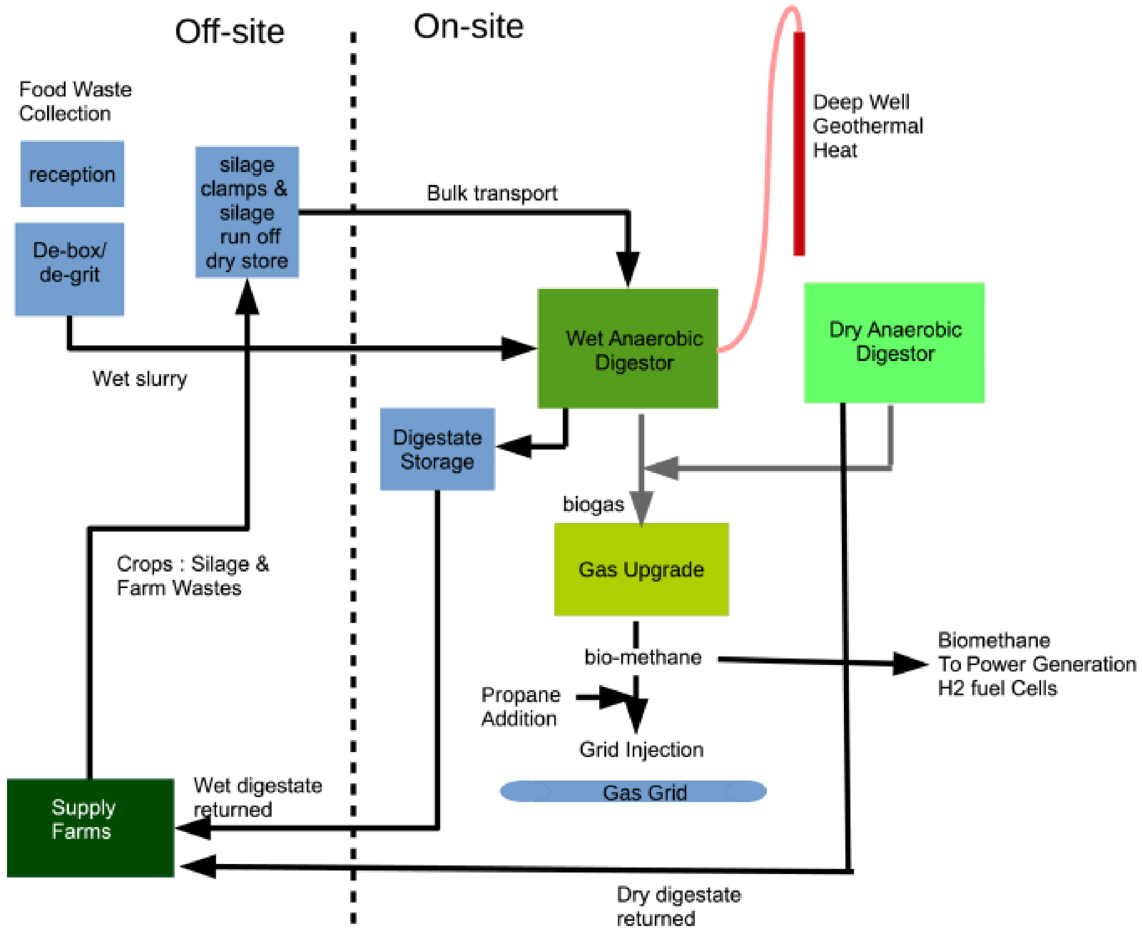

Figure 14 Schematic diagram showing the integration of the geothermal well into the AD unit

INSTALLATION METHODOLOGY

The installation of the system can be split into two principal sections:

1. Drilling and casing the well
2. Fitting the well with DGSW equipment, testing and commissioning

DRILLING AND CASING THE WELL

A 2km vertical well will be drilled at the site and cased to approximately 1,700m. The drilling contract will be structured so that the temperature can be tested at the base of the well prior to the drilling rig being removed from the site. If the temperature is not sufficient for the required delivery at the site then the rig will be sufficiently equipped to continue to drill for up to an additional 600m. For the average geothermal gradient in the UK (2.8C per 100m[47]) this represents the capacity to deliver an additional 17C of temperature contingency if required.

The drilling rig that we propose to use at the site is likely to be the Drillmec HH102 rig. This is a drilling rig that we have had experience of working with in other countries for 2km vertical wells. An example of the rig in operation is shown in Figure 15. This rig is in the United Kingdom and is available for use at the AECC site.

It is important to note that one of the benefits of the DGSW system is that the well contract can be issued and managed under an Engineering Procurement Construction (EPC) contract. This is not standard practice for oil and gas wells but, due to the simplicity of the well design, can be agreed for the DGSW (see section on contracts and insurance). The result of the EPC contract is that costs for the drilling stage of the project can be well constrained.

Figure 15 Example of the Drillmec HH102 that we propose to use at the AECC site

[47] British Geological Survey, UK geothermal resource, 2012

DRILLING METHODOLOGY

The proposed drilling methodology for the AECC site is outlined in the following sections:

SITE SET UP

- Mobilise site perimeter hoarding to site and install around site perimeter
- Lay impermeable “nappy” membrane across site area and install collection sump for surface run-off.
- Lay timber matting across site area to protect ground from any excessive point loading
- Mobilise site welfare facilities and setup onsite i.e. welfare canteen (30 ft.), drying/change room (30 ft.) and toilet block (10 ft.)

CELLAR CONSTRUCTION

- Mobilise heavy plant (excavators and dumpers) to site.
- Excavate and install cellar 3 no. x 1m deep x 2.1m ID concrete rings and install sleeve casing for mousehole.
- Set cellar rings in concrete and install cellar floor c/w 30” casing sleeve for commencement of conductor installation drilling

CONDUCTOR INSTALLATION

- Mobilise shallow auger drilling rig and ancillary equipment (cement grout plant etc.) onto site location
- Set-up and Auger drill from surface to +/- 20m
- Install +/- 20m of 20” J-55 API 5-CT casing and pressure cement grout in place using ordinary class C cement
- Rig down and demobilise auger rig and all ancillary equipment from site

RIG MOBILISATION

- Mobilise drilling rig and all ancillary equipment onto site location
- Rig up drilling unit and layout rig and ancillary equipment configuration as per the agreed layout
- Perform rig acceptance test
- Hold tool-box talk (TBT) and pre-spud H & S meeting to ensure full understanding of the work scope requirements amongst all crew members
- Rig up riser line to the mud shaker system for cutting collection

ESTIMATED DRILLING PROCEDURE

- Fill mud tanks and mix mud as per the mud programme and under direction from the mud engineer.
- Install 20” wellhead connector and 13 5/8” annular. Carry out pressure test.
- Make-up 14 ¾” bottom hole assembly (BHA), run-in-hole (RIH) and spud well
- Drill 14 ¾” to section TD (+/- 500m)
- Pull-out-of-hole (POOH) and laydown 14 ¾” BHA
- RIH +/- 500m of 10 3/4” J-55 API 5-CT casing, rig-up cement lines, prepare cementing equipment
- Run in hole drill pipe c/w stab in tool and cement 10 ¾” casing to surface utilizing stab in method of placement as per 3rd party supplier cementing programme

- Wait-on-cement (WOC)
- Install wellhead connector onto 10 ¾" casing and full 13 5/8" BOP stack (annular and double gate) – Function and pressure test
- RIH 9 ½" bit and drill out shoe track and float shoe
- Circulate and condition mud and perform FIT
- 27) POOH, make-up and RIH 9 ½" BHA
- 28) Drill 9 ½" to well TD of 2,000m
- 29) Rig-up wireline logging unit and run temperature and caliper logs to TD
- 30) RIH and install liner hanger system onto 10 ¾" casing at 350m and RIH +/- 1350m of
- 7" J-55 API 5-CT liner casing
- 31) Empty mud tanks and rig down rig and ancillary equipment
- 32) Demobilise from site rig and all ancillary equipment

SITE DISMANTLING

- Install temporary fence around cellar for ongoing work
- Demobilise site welfare facilities from site
- Remove timber matting from site area and demobilise from site
- Remove "nappy" membrane from site area and demobilise from site. Empty site runoff from collection sump
- Take down site perimeter hoarding and remove from site

HANDLING AND DISPOSAL OF WASTE

All surplus waste materials will be moved from the work areas and disposed of by a specialist drilling waste removal company from Aberdeen.

- Site waste management plan will be in place
- All COSHH details to be retained on-site.

TESTING AND COMMISSIONING

Once the well has been drilled and cased, the DGSW equipment will be installed as per the recent (2014) installation in a 2.6km well in Cornwall. The installation process will take approximately two weeks to complete, during which a standard 40 Tonne crane will be on the site at all times.

Once the equipment has been installed, the well will be tested with a Thermal Response Test rig that was designed and built by Geothermal Engineering Ltd in 2014. The rig has the capacity to extract up to 400kW of heat and test the thermal performance of the well by simulating different building demand cycles. The unit is the largest thermal response test equipment in the country (approximately 10 times larger than similar rigs) and has been built exclusively for deep geothermal single well testing. The rig and connections to the rig can be seen in Figure 18, Figure 19 and Figure 20.

Once the Thermal Response Test rig has been connected to the DGSW we will be able to test the performance of the submersible pump, the drawdown in the well under various bleed flow conditions, the nature of the geothermal fluid under abstraction / rejection at different temperatures and the thermal response of the system to various building loads. The system operation and pump control can then be optimised for use at the AECC. This testing and commissioning phase for the system will take approximately 4 months to complete.

We believe that Geothermal Engineering Ltd is uniquely positioned to undertake these types of tests and the results will be highly beneficial to both ensuring the optimum performance of the well at the site and to assisting the development of deep geothermal energy in Scotland as a whole.

Figure 16 Completed well-head connections to the Thermal Response Test unit

Figure 17 Thermal Response Test unit and connected energy abstraction fans

Figure 18 Thermal Response Test unit showing heat exchanger and central control panel

REGULATORY REVIEW

In January 2016, the Scottish Government produced the regulatory guidance document "Geothermal Heat in Scotland"[48]. In conducting our review, we have followed the guidance within this document and we have undertaken preliminary consultations with the three key bodies who would have responsibility for the "regulation and control of activities" for the specific project near Aberdeen.

At the proposed site there will be two regulatory bodies whose requirements the DSGW system must legally comply with: the Scottish Environment and Protection Agency (SEPA) and Aberdeen City Council (ACC). Further to this, although not legally required, the well construction and drilling methodology should also be compliant with and approved by the On-Shore Health and Safety Executive. Aberdeen is not within a Coal Mining locality and therefore no consultation with the Coal Authority would be necessary for this specific project.

We have contacted all three of these agencies and the requirements for the AECC site are understood to be as follows:

SCOTTISH ENVIRONMENT AND PROTECTION AGENCY (SEPA) REQUIREMENTS

The laws and regulations governing Deep Boreholes fall into two broad categories. The first is General Scottish law, in which the specific laws and systems relating to the management of the Scottish Water environment are termed the Water Framework Directive (WFD). The second is the "Water - Controlled Activities Regulations (CAR)" which is overseen by SEPA. Licences for drilling and abstraction from deep boreholes are controlled by SEPA and two application forms must be submitted, along with all the supporting studies and documentation detailed in the forms. For boreholes greater than 200m, details on the depth, geology, casing, cementing, drilling fluids and chemicals will need to be provided to include:

- National Grid reference for the top of the well head and for the bottom of the borehole (if there is any lateral deviation underground)
- Details and locations of any other nearby deep boreholes, faults or mine workings
- Approach for dealing with drilling fluid loss and/ or artesian flow
- Details of integrity testing of the borehole to ensure proper construction
- A Water Features Survey to include abstractions, surface waters, springs and wetlands within 1200m of both the top and the bottom of the borehole.
- Baseline environmental monitoring
- Details of proposed ongoing environmental monitoring to ensure integrity of the borehole.
- Details of an Action Plan in case of adverse Environmental impact
- Decommissioning plans – temporary sealing and long-term decommissioning

If the abstracted groundwater contains naturally occurring radioactive materials (NORM) then a Radioactive Substances Act (RSA) authorisation may be required for the discharge. This applies if the borehole is associated with a NORM Industrial Activity (oil and gas etc.). This would also require sampling of the groundwater prior to abstraction.

The abstraction and recharge licences for a deep geothermal single well will be discussed once we have drilled the well and understand the level of potential bleed flow that the well will sustain. The nature of the discharge

[48] Scottish Government: Regulatory Guidance - Geothermal Heat in Scotland. January 2016

licence will also be dependent on the quality and chemical composition of the geothermal water. This will be determined once the well has been drilled.

SEPA have indicated that the application process is likely to take approximately 4 months to complete. However, given that this project would be the first application of this type, we believe that 6 months might be more appropriate.

For the licence application the following documentation will need to be completed:

- Deep borehole drilling: Regulatory Method (WAT-RM-11) Licensing Groundwater Abstractions including Dewatering.
- Licence application for deep boreholes: Form A, Form K
- Water features survey
- Groundwater monitoring (if required). SEPA Technical Guidance Note Hydrogeological Risk Assessment for Landfills and the Derivation of Control and Trigger Levels

For the AECC site, some of the environmental studies have already been completed as part of the recent planning application for the new centre. We also have documentation relating to the recent application to the Environment Agency in England for a similar type of well which will be a useful reference point.

REQUIREMENTS OF ABERDEEN CITY COUNCIL

Arup recently worked with Geothermal Engineering Ltd on a Planning submission for a deep geothermal single well system at the Crewe Campus of Manchester Metropolitan University. The project received planning permission on the 23rd of September 2015. We intend to use the documentation developed for this project as a guideline for the AECC site.

CONSENTING REGIME

The consenting for any Deep Geothermal Single Well (DGSW) in Scotland would be under the remit of the Scottish planning regime, notably the Town and Country Planning (Scotland) Act 1997 and the Planning etc. (Scotland) Act 2006. No electricity is to be produced via the well, which will only produce heat from water at a peak thermal output of approximately 400kW or 2GWh per annum. As such, no consent would be required under the Electricity Act 1989.

Unlike hydraulic stimulation or 'fracking' the DSGW does not require the breaking up of the rock to create a permeability pathway in order to operate. Due to public concerns surrounding fracking and the current Scottish Government 'Moratorium on Fracking' in Scotland[49], it is considered that single well technologies with no requirement for underground hydraulic stimulation, are most likely to advance through the planning process.

The following sections report the key aspects of the consenting regime with respect to environmental impact assessment (EIA), habitat regulations assessment (HR) and planning application requirements. Further information on the consenting regime can be found in current regulatory guidance on the matter.

[49] http://news.scotland.gov.uk/News/Moratorium-called-on-fracking-1555.aspx

ENVIRONMENTAL IMPACT ASSESSMENT

The drilling of a DGSW is potentially a form of development that requires environmental impact assessment (EIA) under the Town and Country Planning (Environmental Impact Assessment) (Scotland) Regulations 2011. The basis for whether EIA is required is dependent on whether the proposal constitutes Schedule 1 development (types of development where EIA is always required) or Schedule 2 development (types of development where EIA may be required based on certain criteria).

Geothermal wells are unlikely to be categorised as Schedule 1 development, but they are potentially classed as Schedule 2 development under section 2 (extractive industries) part (d)(i), or section 3 (Energy Industry) part (a). Whether or not they are Schedule 2 development depends on the proposed development breaching either of the following criteria:

1. The area of works exceeds 1 hectare if classed as an Extractive Industry or 0.5 hectares if classed as Energy Industry; or
2. The drilling is within 100m of a controlled source (surface water); or

Given the proposed realignment of controlled waters within the AECC site, there is the potential that the proposed location for the geothermal well could be within the 100m limit of a controlled source depending on the receiving environment and the scale of development. Discussion with ACC has identified that they do not believe that the any of the water courses within or near the site would fall under the definition of 'controlled waters' as per the EIA regulations although a screening opinion should be submitted at an early stage. The Council expect that the AECC would be looked at cumulatively rather than as a main part of any EIA for the geothermal development.

HABITATS REGULATIONS ASSESSMENT

Depending on proximity to, and likelihood of affecting, Natura 2000 sites (including Special Protection Areas, Special Areas of Conservation and Ramsar sites), the DGSW may require a Habitat Regulations Assessment (HRA) under the Conservation (Natural Habitats, &c.) Regulations 1994, as amended. Under HRA, the qualifying interests of the site will be assessed to determine whether significant effects resultant from a development are likely to affect the integrity of the site, and if so, how they can be mitigated.

Proposals where mitigation of significant effects is not possible will only be permitted where there are no alternative solutions and where there are reasons of overriding public interest relating to the proposals. Where a European priority species or habitat is affected, reasons of overriding public interest can only relate to human health, public safety, beneficial effects of primary importance for the environment, or other reasons subject to the opinion of the Scottish Ministers.

Future consultation with Scottish Natural Heritage will determine the requirement for any HRA associated with the DGSW.

PLANNING APPLICATION

Under the consenting regime, a full planning application will be necessary in line with the requirements of the Town and Country Planning (Scotland) Act 1997 and the Planning etc. (Scotland) Act 2006. Under the 2006 Act, planning applications in Scotland are either classed as national, major or local development. These developments are defined below in Figure 21.

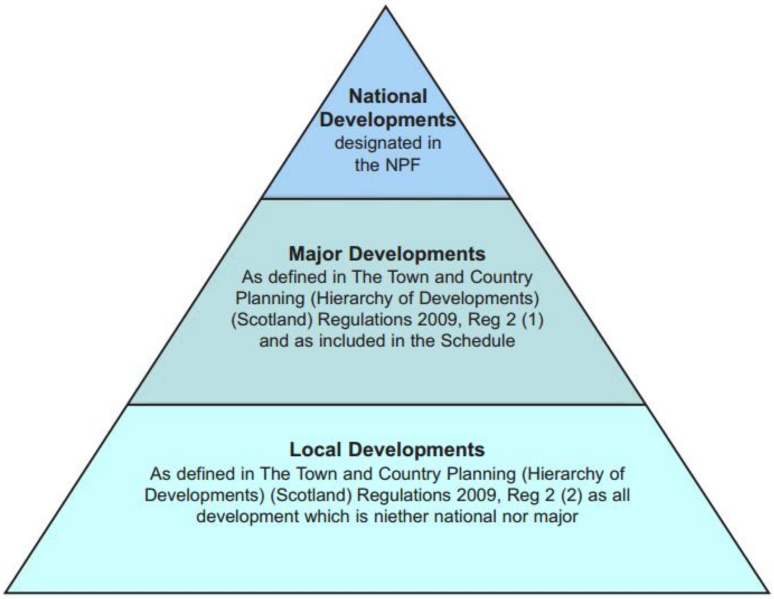

Figure 19 Hierarchy of planning applications in Scotland[50]

Any future planning application for a geothermal well at the AECC site is likely to be a local development, which as described above, may need to be supported by an EIA. The application would be submitted to ACC and would need to include any other relevant information included on the ACC planning application validation checklist.

Following discussions between Arup and Aberdeen Council, our Planning application for the AECC would cover the following topics:

1. Introduction
    a. Background
    b. Need for development
    c. Geothermal heat
    d. Project background
2. Context
    a. Site description
    b. Site character
    c. Surrounding uses
    d. Landscape
    e. Climate
    f. Transport access
    g. Utilities
3. Environmental issues
    a. Noise
    b. Transport
    c. Landscape
    d. Contamination
4. Planning policy context
    a. Introduction
    b. National policy and guidance
    c. Local policy

d. Planning history

Aberdeen Council currently has no specific guidance or policy documents on geothermal projects. However they have stated that the principle of renewable energy sources is supported generally by both Scottish Government national guidance and the Councils Local Development Plan. The most relevant LDP policy would be Policy R8 (Renewable and low carbon energy developments). The Council anticipates there being some public or Councilor interest in such a development as it is not something the city has any experience of. Therefore, although it is likely that there proposal would be categorised as a local development rather than a major development, which has statutory consultation, some level of public consultation, which could be agreed with the Council, would be beneficial. The application would be looked at independently of the AECC application as either could potentially take place without the other.

ON-SHORE HEALTH AND SAFETY EXECUTIVE (HSE)

We have discussed the deep geothermal single well with HSE as part of the development at the site in Crewe. For onshore drilling for **petroleum** there are two main sets of Health and Safety legislation:

1. The Borehole Sites and Operations Regulations 1995 (BSOR)
2. The Well Aspects of the Offshore Installations and Wells (design and Construction, etc.) Regulations 1996 (DCR)

From a legal point of view there is no need to submit any information on a geothermal well to the Health and Safety Executive to comply with the Borehole Sites and Operations Regulations 1995 [BSOR] unless it is located in a mining area. Currently, newer technologies such as geothermal wells are a grey area as far compliance with legislation is concerned. However, developers will need to comply with the Construction Design and Management Regulations and other Health and safety legislation.

As deep drilling always has inherent risks, HSE has proposed that we should work to the highest standards available, namely the BSOR. This would include submitting the following to HSE as a matter of course. We would also suggest that other potential projects in Scotland follow the same course. The information required by HSE is listed below:

		Minimum Information Required for an Onshore Notification
1	*Name and address of operator*	▪ Operators name & Operators address ▪ Name and address of Operator of Site if different to above
2	*Particulars of the type of well, its number and its name*	▪ Exploration, appraisal or development ▪ Function to which it will be used if development well, e.g. oil producer, gas producer, water injection ▪ The DTI well number. [The DTI numbering system is to be used prior to spud]
3	*Particulars of the rig or other plant which is to be used in connection with the operations on the well*	▪ Name of Drilling Contractor/Name of rig ▪ Layout and brief description/capacities of the main equipment, e.g. derrick rating, drawworks hoisting capacity, high pressure mud pump(s), coiled tubing unit, mud storage, solids control equipment, well testing package
4	*Particulars of the surface equipment and of the circulating*	▪ Details of the Well control equipment [BOP, Rotating head, Diverter, Choke Manifold, Mud/gas separator] including size and pressure rating.

	fluids to be used to control the pressure of the well	▪ Details of BOP control unit, e.g. accumulator capacity and sizing ▪ Generic fluid type for drilling each section of hole ▪ Mud weight for each hole section ▪ Generic fluid type for testing, completion, workover operation ▪ Mud weight for each operation type; e.g. completion, testing, workover, etc.
5	*Particulars, with scale diagrams where appropriate, of -* (A) *the Ordnance Survey National Grid ref of the location of the top of the well* (B) *the directional path of the borehole* (C) *the terminal depth and location* (D) *its position and that of nearby wells and mine workings relative to each other*	▪ National Grid reference of surface/target locations ▪ Latitude & longitude of surface/target locations ▪ Directional plot for non vertical wells: to include vertical section and horizontal section ▪ Measured terminal depth and vertical terminal depth ▪ Map showing the surface location and entire lateral position of well and all others in the vicinity [either at surface or at sub surface level] together with any mine workings ▪ Confirmation that the potential of collision of relevant wells or mine workings have been looked at and that plans are in place to minimise the risks
6	*A description of operations to be performed and programme of works including -* (A) *the dates on which operations on the well are expected to start and finish* (B) *a diagram showing details of the intended final completion or recompletion of the well*	▪ Estimated start/finish dates or duration ▪ List of operations to be carried out, e.g. re-enter, plug back, sidetrack, test, drill, workover, etc. ▪ Summary of the well programme which details the major steps related to safe operations: all main safety related issues would be addressed, e.g. casing pressure details, leak off tests and formation integrity tests to be carried out and required minimum values, cementing programme and method of confirmation of cement tops, testing of barriers prior to removal of BOPs, testing of BOPs, etc. ▪ The operational state at the end of operations should be one of completed, abandoned or suspended ▪ A schematic of the intended final well state should be included
7	*A description of –* (A) *any activity during operations on the well which will involve a risk of the accidental release of fluids from the well or reservoir; and* (B) *such hazards*	▪ Identify those hazards and activities connected with the particular well which have the potential to cause a major accident, e.g. shallow gas, H2S, high pressure, lost circulation, underbalance drilling, DST ▪ Identify where SIMOPS are to take place at drilling sites and the policy covering SIMOPS
8	*In the case of a well which is to be drilled* (A) *particulars of the geological strata, and formations and fluids within them through which it may pass and of any hazards with the potential to cause fire, explosion or a blow-out, which they may contain*	▪ Geological column from surface to TD, detailing measured and vertical depths ▪ Est. formation pressures in all permeable and porous zones ▪ Est. fracture pressures at intended casing points ▪ Prognosed fluid types [e.g. gas, condensate, oil, etc.] presence of gas cap etc., fluid gradient, presence and concentration of toxic gases [e.g. CO2, H2S, etc.] ▪ Identify potential producing formations ▪ Confirm a specific shallow gas assessment has been completed ▪ Particular hazards associated w/well, e.g.: Major loss circ zones, overpressures, salt domes

	(B) *the procedures for effectively monitoring the direction of the borehole and the effects of intersecting nearby wells:*	▪ Survey programme for each section of hole ▪ Confirmation that there is a system for programming surveys and for comparing survey data with that of nearby wells and that there are criteria for taking action ▪ List nearby wells, which are of special significance with respect to the drilling of the particular well. Provide separation factors for the significant well
	(C) *particulars of the design of the well, sufficient to show that it takes account of matters in sub paragraph a) of this paragraph, and that it will, so far as is reasonably practicable, be safe*	▪ Est. max whd press, during operations ▪ Summary of hole sizes/section TDs ▪ Summary of casing strings to be run, including setting depth, size, weight, grade and couplings. Kick tolerance and specification if not API grades. Provide details of the wellhead and Xmas tree ▪ Details of cementing prog/casing string and for any abandonment or suspension to be carried out ▪ Details of testing; surface equipment and shutdown systems ▪ Schematic diagram of the proposed completion
9	*In the case of an existing well-* *(A)* *a diagram of the well* *(B)* *a brief history of the well including a summary of previous operations and any problems encountered; and* *(C)* *its present status and condition*	▪ Current casing and completion or suspension diagram ▪ List, with dates, of major operations on the well e.g. spud date, drill and suspend, re-enter and redrill, re-enter and complete, major workovers ▪ Operational state is abandoned, suspended or completed ▪ Details of any known or suspected safety related failure or defect in the well e.g. corrosion problems, Xmas tree valve failure, DHSSV control line failure ▪ Details of barriers and fluids in the well
10	*In the case of an abandonment operation details of the proposed sealing or treatment*	▪ Current casing and cementing programme ▪ Depths of hydrocarbon bearing strata or aquifer ▪ Number and location of barriers ▪ Testing of barriers ▪ Monitoring of pressure build-up

HSE have also advised us that we should work to the spirit of the DCR. This set of regulations covers a life cycle approach of a well from concept / design, construction, operation, maintenance through to final abandonment. This includes a requirement for a well examination scheme to be in place where an independent and competent person reviews the well design. Again, we would suggest that any geothermal drilling project in Scotland adheres to this process.

REVIEW OF CONSENTS AT CREWE PROJECT

For a recent DGSW demonstration project near Crewe, the Planning Consent was achieved within 3 months with broad Council and local support. The site was located in an urban area and therefore was a test case for the development of DGSW projects. All documentation associated with this application will be shared with Aberdeen City Council if the project moves forward.

PUBLIC PERCEPTION AND COMMUNITY ENGAGEMENT

In Scotland, there is significant public concern about potential deep subsurface developments such as shale gas, coal bed methane or the capture and storage of carbon underground. There are clearly contentious aspects to these types of developments such as hydraulic stimulation, fracking and contamination risks but it is also the case that the lack of knowledge and technical understanding of the deep subsurface on-shore in Scotland leads to an irrational fear and misconception of the "*alien subsurface*". This section considers the issue of public perception of deep geology and discusses the potential ways to improve knowledge and acceptance. It also considers how low risk deep geothermal developments such as the AECC DGSW could provide an opportunity to assist in improving public perception of deep geological projects.

The interpretation of the subsurface is a challenging subject for geologists and engineers who review and analyse technical information to develop deep ground models in 2 or 3 dimensions. Without training or specialist knowledge in geoscience it can be difficult to answer questions such as "*what does the subsurface look like*?" or "*what is actually present beneath our feet*?" On-going research at Plymouth University is asking these sorts of questions to members of the public without a geoscience background to understand the psychological response to the subsurface and current perception of what the subsurface is. The recent findings are interesting, with responses including the drawing of irregular nonsensical shapes and lines and the use of words such as "*dirt*" and "*dark*". The responses point to an emotive rather than an informed understanding, which suggest that the perception of the subsurface is irrational, rather than from an informed perspective. Therefore, there is an argument that better public understanding through education and engagement is needed to facilitate the development of a more rational viewpoint.

LOW RISK TECHNOLOGY

Since January 2015 there has been a Moratorium on the consideration of potential unconventional gas projects in Scotland. The Moratorium is to allow further research to be carried out into the potential health and safety impacts of shale gas development. Going forward, we consider that it would be prudent that deep geothermal projects in Scotland should be of a very low technical, environmental and commercial risk. To build trust and community acceptance, we believe that any projects should avoid the requirement for potentially contentious fracking or hydraulic stimulation to create deep permeability pathways in order to operate. The DGSW technology does not require any form of hydraulic stimulation or fracking or use any chemicals to enhance the performance of the rock.

EFFECTIVE COMMUNICATION AND COMMUNITY BENEFITS

Effective and educational community engagement is vital to ensure that all members of the public understand how a proposed technology will work. Any engagement programme also needs to categorically alleviate any concerns regarding the potential risks that may be associated with that technology. In August 2015, Geothermal Engineering Ltd and Arup undertook community events in Cheshire East to discuss the proposed DGSW technology and its installation at the Manchester Metropolitan University Campus in Crewe. The community events were extremely successful, key questions from the public included "*does this require fracking?*" and "*do you use chemicals?*" which again highlights the public's emotive fear of the subsurface. The ability to answer questions clearly and state that the technology requires no fracking, hydraulic stimulation or use of chemicals left the public with a positive perception of the technology and helped remove the underlying fears and misconceptions.

The proposal for this project is to provide heat to the on site Anaerobic digestion plant *and* sustainable low carbon heating for residential dwellings in close proximity to the AD plant via a low temperature geothermal heat network. This is a strong community benefit and will enable us to engage the local community in the discussion about deep geothermal drilling and heat supply.

PUBLIC INTERACTION WITH THE SUB-SURFACE

We believe that any feasibility study for a deep geothermal project needs to consider the available opportunities to engage, inform and educate the public on the subsurface when the technology is installed and operational. The AECC development offers a great opportunity to create a public exhibition of the technology using a wide variety of media. Discussions with Iain Stewart, Professor of Geoscience Communication at Plymouth University, identified that possible methods of education and engagement should include media that challenges the public to consider the subsurface and engage with it. This needs to go beyond posters and diagrams and should be interactive to make the public feel like they have been transported deep below ground. For instance, the recording of noises from within the borehole using geophones and displaying tele-viewer video is considered to offer an opportunity to display the sights and sounds of the subsurface in a novel way that challenges current public perceptions and confronts people with the reality of what is actually below ground. An active example of this is an art exhibition in Germany, which plays the sounds from the base of the 9km deep Windischesschenbach borehole. This aims to challenge the perceptions of the deep underground and, in the opinion of the artist Lotte Geeven, acts as an "*engine for new thoughts and ideas*". An exhibition could also include cores from the borehole at a range of depths so that people can touch and feel the deep earth and obtain a tangible appreciation of what deep geology looks and feels like.

DEEP GEEOTHERMAL EXHIBITION AND COMMUNITY OUTREACH

As an exhibition and conference centre, the AECC lends itself very well to this type of working demonstration and provides an opportunity for a 'Deep Geothermal Energy Exhibition'. The exhibition would engage the public and be very accessible to school children/ university students who could interact and engage with the technology. Further, project partners St Andrews University operate the GEOBUS outreach program that takes geology education to high schools in the Fife area where geology is not a subject on the curriculum and aims to provide an educational catalyst to an interest in the geosciences. A 'Deep Geothermal Energy Exhibition' could work with the GEOBUS outreach program to bring school children to the exhibition so that they could embrace and experience the technology and become inspired to question what the subsurface is. We consider that this offers possibly the greatest and widest opportunity for community engagement of any geothermal development in Scotland, as the number of people that could visit and be educated by the DGSW exhibition at the AECC would be in the thousands.

The showcase venue at the AECC also offers the potential to demonstrate the technology to the Aberdeen Oil and Gas Industry through the major offshore oil and gas conferences that will take place at the venue from 2017. The creation of a 'Deep Geothermal Energy Exhibition' will enable the potential synergies, crossover potential and Scottish supply chain development opportunity discussed later in this report to be showcased in the most attractive way possible.

COMMUNITY ENGAGEMENT PLAN

As part of the implementation phase of the project we would conduct a full Public Consultation and Engagement exercise. We recently ran a very successful campaign for a very similar project at a site in Crewe, near Manchester. Part of this process included a full day of public consultation that was well attended (Figure 22). Despite the project being situated in an urban area, the local residents were 100% in favour of the project. One of the primary concerns (a full list of concerns is included in Table 4) expressed during the consultation was whether the project would involve any 'fracking'. We believe that for a project to achieve planning permission and public acceptance it is very important to be able to categorically state that no 'fracking', 'hydroshearing' or 'stimulation' (either mechanical or chemical) will occur during the project. Public acceptance of deep geothermal technology will hinge on how well the first projects are developed. We strongly believe that the first deep geothermal projects in Scotland should not involve any form of stimulation or any injection of water into rock under pressure. We have already seen what happened to the shale gas industry in England after one well was drilled and stimulated and we cannot afford to set the deep geothermal industry back many years by making the same mistakes.

Figure 20 Public engagement at the Crewe site

Principal concerns	Responses
Duration of the drilling project	The duration of the project was described as being a maximum of seven weeks, including two periods of drilling lasting about 4-5 days and 10-12 days respectively. All attendees considered the short-term duration of the project to be acceptable, and were generally positive about it being undertaken over the winter period (late November 2015 - mid January 2016).
Residual plant and equipment (specifically visual impact and noise);	Concern was expressed over the likelihood of drilling equipment being a permanent feature of the project, and the potential for noise impacts arising from the operational (post-drilling) period. It was explained that the tallest structure (the drilling rig, at up to 26m height) would only be present on site for a short duration (approx. 3-4 weeks in total), and that following its removal the well-head plant would consist of two pipes and associated valves of maximum 1.5m height. The noise levels likely to be encountered during the operational period were described as a low frequency hum generated by the valve and monitoring equipment that would be inaudible at a distance of around 2m. All attendees were reassured by the minimal long-term impacts of the proposals, and expressed a generally positive view of the project.
Relationship to hydraulic fracturing (Fracking);	A few attendees mentioned concerns over the use of hydraulic fracturing, especially for gas or oil production. It was stressed that there is no intention to explore or exploit hydrocarbon resources since the whole purpose of the venture is to test low-carbon energy viability. It was further explained that the underlying geology and design of the well-bore are not conducive to hydrocarbon production, irrespective of the use of hydraulic fracturing.
Drilling noise;	Some residents expressed concerns over noise impacts associated with the drilling process. It was explained that day-time noise levels from the site would be lower than existing ambient noise levels, resulting in no adverse effect. The need to undertake 24-hour drilling activities was explained in terms of borehole stability and adverse effects of intermittent starting of the drilling process. It was accepted by all attendees that 24-hour drilling would be necessary. Night-time noise levels were described as a continuous hum, similar to a diesel generator fitted with noise attenuation measures, such as those used in most road works. Since the drilling would be undertaken during the winter months, it was explained that closed windows would reduce external

	noise levels by between 10 -30 dB. It was also explained that under calm weather conditions residents would be aware of a background noise, however this would be unlikely to be intrusive and would operate for relatively short durations. No attendees maintained objections to the anticipated noise levels, while some expressed the view that this would be a negligible impact that would be outweighed by the benefits of the proposal.
Safety.	Concern was expressed over the potential for blow-outs or explosion associated with drilling. It was explained that the geological data indicates that the presence of pockets of gas is extremely unlikely. This has been confirmed by a Preliminary Risk Assessment for ground contamination undertaken as part of the project (accompanying document to the planning application). The drilling process also includes a blow-out prevention device which triggers an immediate shut-down of the drill in the event of pressures inside the borehole reaching a specific threshold.

Table 4 Principal concerns expressed by residents during the public engagement exercise

DRILLING CONTRACTS AND INSURANCE

This section provides an overview and discussion of the contractual and insurance options for the drilling phase of a geothermal project and the most appropriate route for the AEEC site. As the majority of the cost of a deep geothermal project is the drilling phase, the contractual structure needs to be robust and the most suitable for the project. As geothermal developers are often small with limited balance sheets, the terms of the contract, particularly with regards to additional cost liability, must be favourable to the developer ("Operator" in contractual terms). The definition and distinction between geological and technical risk and, above all, the allocation of that risk between the drilling Contractor and the geothermal Operator is key to delivering a successful project. There are many examples of projects that have failed, even in the UK, due to a lack of clarity on the contractual obligations when aspects of the drilling do not go according to plan. If the Operator does not have sufficient cash reserves or is not effectively insured, the project will fail.

A typical drilling operational structure for a deep well is outlined in Figure 23. The potential variations to this structure will be discussed in subsequent sections.

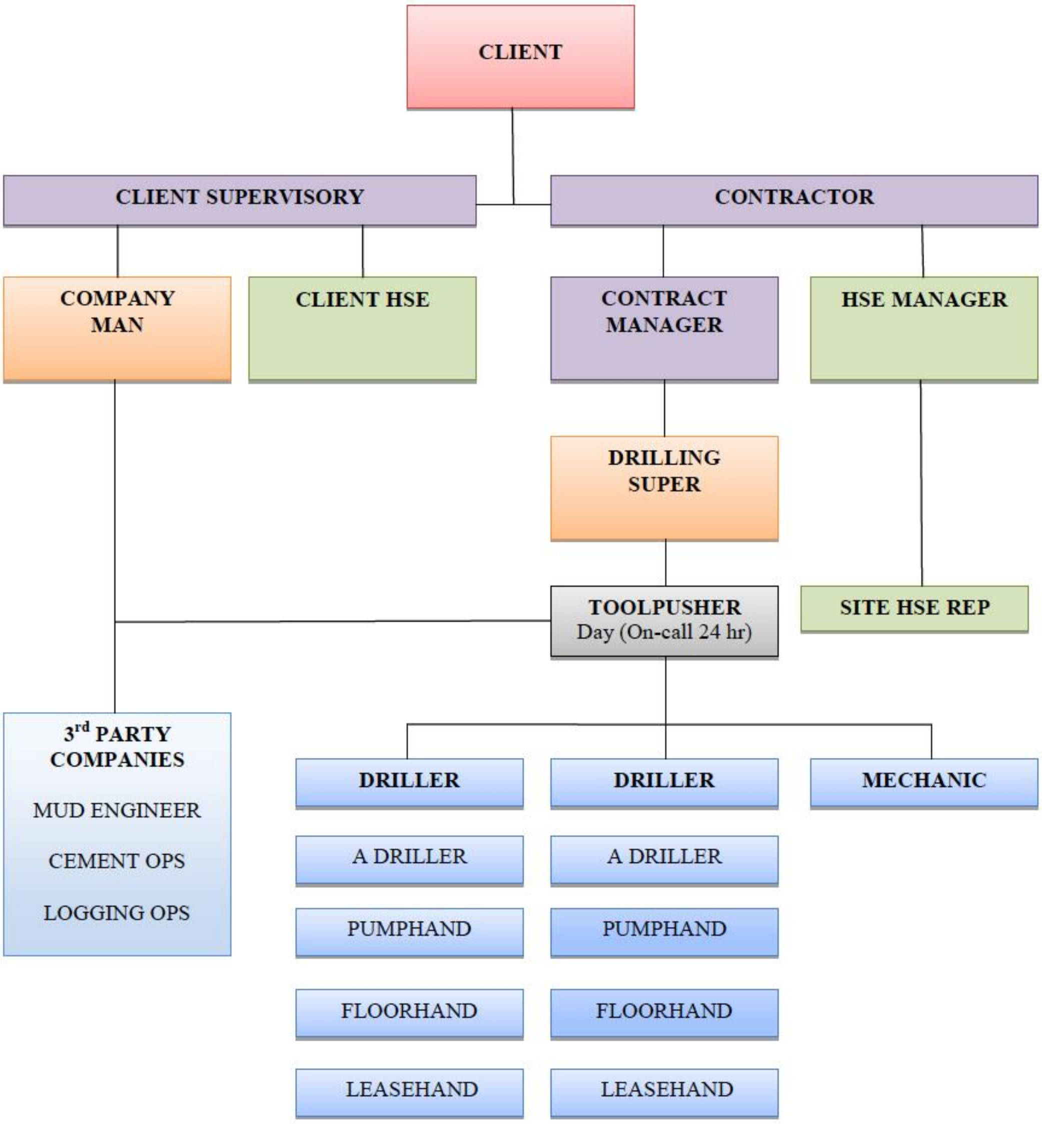

Figure 21 Typical deep drilling operational structure

CONTRACT MODELS

Within the European drilling sector there are two principal types of contract for drilling geothermal wells:

- Turnkey or so termed ‘Engineering, Procurement, Construction’ (EPC) contract
- Day Rate Contract

Shallow (<1,000m) geothermal projects and water wells have traditionally been drilled under a **Turnkey Contract**. This means that a drilling contractor delivers a completed well for an agreed price. The drilling contractor therefore takes on all of the drilling risk. As geothermal heat projects were often undertaken by building developers or local municipalities with little geothermal experience, the Turnkey contract allowed the Operator to pass on all technical risk and responsibility to the Contractor until completion and handover of the project.

However, as drilling becomes deeper and more complicated (particularly with directional drilling and hydrocarbon risks) Turnkey contracts become less common. Instead, **Day Rate** contracts are used. Under a day rate contract, the drilling contractor provides personnel with specialist drilling engineering expertise and the Operator provides personnel responsible for the coordination and management of the project. It is effectively a time and materials contract.

Geothermal projects with deep drilling and deviated wells require higher performance drilling rigs and greater deep drilling expertise. This has resulted in contractors from the oil & gas sector being used for the project due to their deep drilling experience. Many contractors from the oil & gas exploration sector now see the drilling of geothermal wells as a very attractive market and regularly compete on an international scale for contracts. In general, their contractual experience has been based on day rate contracts, that transfer much more of the risk to the Operator. This is acceptable in the oil and gas industry, where Operators typically have substantial balance sheets and an in-house team of drilling and reservoir experts. This is generally not the case for geothermal Operators that often need to arrange sufficient insurance cover (where available) to pay for any unexpected changes to the drilling programme and hire a team of specialist consultants. Both of these types of contracts are explored in more detail in the subsequent sections.

The single well system planned for the AECC has been designed to be a simple drilling operation (a vertical well with no deviation) and standard casing diameters/ cementing. It is not designed to operate under pressure and does not need a bespoke cementing design. The preference is therefore to proceed with Turnkey or EPC contracts that allocate risk to the driller and mean that the well can be completed for a fixed price. This is something that we have been exploring in detail with drilling and construction contractors as part of other projects we are developing.

TURNKEY CONTRACT

Due to the higher level of risk borne by the Contractor, the cost of a Turnkey contract can be higher than that initially quoted for a day-rate contract. The amount of the additional cost is also dependent on the assumed responsibilities and technical complexity of the drilling program. Where sub-contracted services are required the contractor will typically include a handling fee. From our experience this value typically lies between 10% and 15%.

Although these contracts are ‘fixed price’ technically intensive and therefore costly problems during drilling (e.g. equipment loss & damage and drill fluid loss) can lead Contractors to claim costs as issues relating to geological conditions, which, depending on the wording of the contract, may be borne by the Operator or Contractor. The proving/disproving of these types of claims is commonly the responsibility of the Operator and therefore the wording of the contract needs to be precise and agreed by all parties prior to commencement of drilling.

Under a Turnkey contract, a drilling contractor normally seeks to complete the well quickly (and problem free) as the contract will typically include a deadline for completion of the works.

DAY RATE CONTRACTS

A day rate contract can be split into two categories:

- Day rate contract without a main contractor
- Day rate contract with a main contractor

For both types of contract, the time management (and subsequent total cost) is controlled by the Operator, who also carries the down-hole risk. The Contractors are often incentivised (through bonus payment schemes) to provide services more efficiently to avoid an excessive number of days and therefore cost, being allocated to drilling. The possibility of negotiating an incentivised contract will depend on the complexity of the well and the prior knowledge of the geological conditions.

DAY RATE CONTRACT WITHOUT A MAIN CONTRACTOR – MULTIPLE CONTRACTS

Under a day rate contract (without a main contractor) the drilling contractor's responsibility is reduced to the operation of the drilling rig and the provision of suitably qualified personnel.

The drilling contractor would typically operate under instruction from the Operator with coordination of the delivery from the Operator appointed supervisory team (or Company Men).

The drilling risk in this case is exclusively borne by the Operator and therefore the contractor is not required to add any risk related supplements. Further, any handling surcharges for service and delivery are avoided as the contracts between the service companies and the Operator are direct. Figure 24 and Figure 25 below provide an overview of the contract and project management structure for a day rate contract model without a main contractor.

This type of structure is typical for an oil and gas well where trained personnel can be provided by the oil and gas company to design the well and monitor/ interpret all aspects of the drilling operation. Further, the oil and gas company will have standardised contracts for all of the sub-contracting entities involved. For a geothermal well, the Operator will need to locate and employ suitably qualified staff prior to tendering a contract as well as employing these staff throughout the drilling operation. The geothermal Operator will also need to develop all of the contracts for the project using experienced oil and gas lawyers. This process can add significant time to the development of a project.

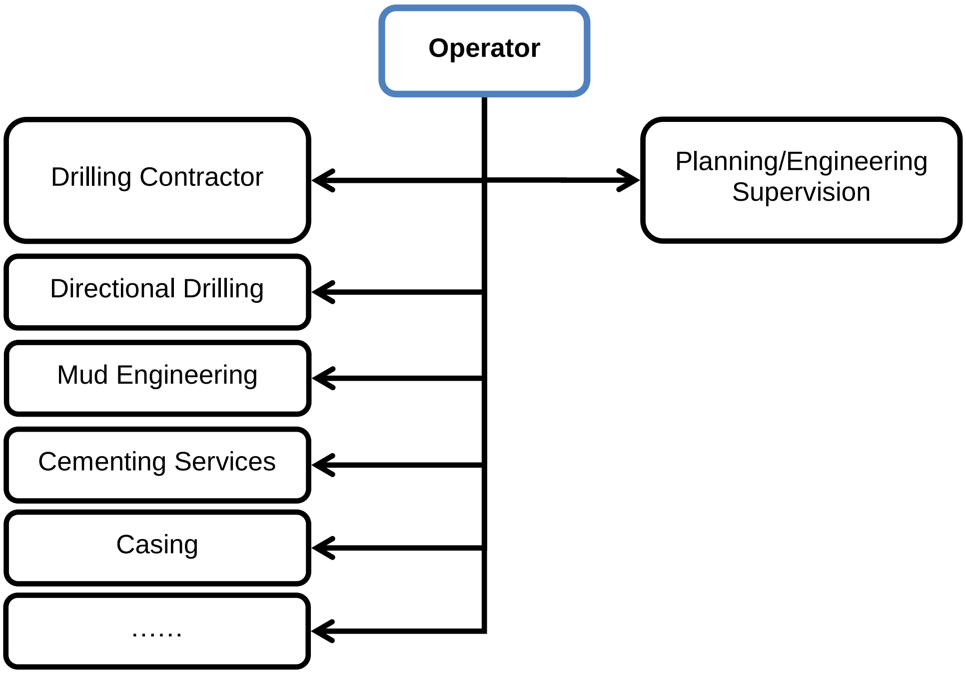

Figure 22 Contract Structure under a day rate without Main Contractor

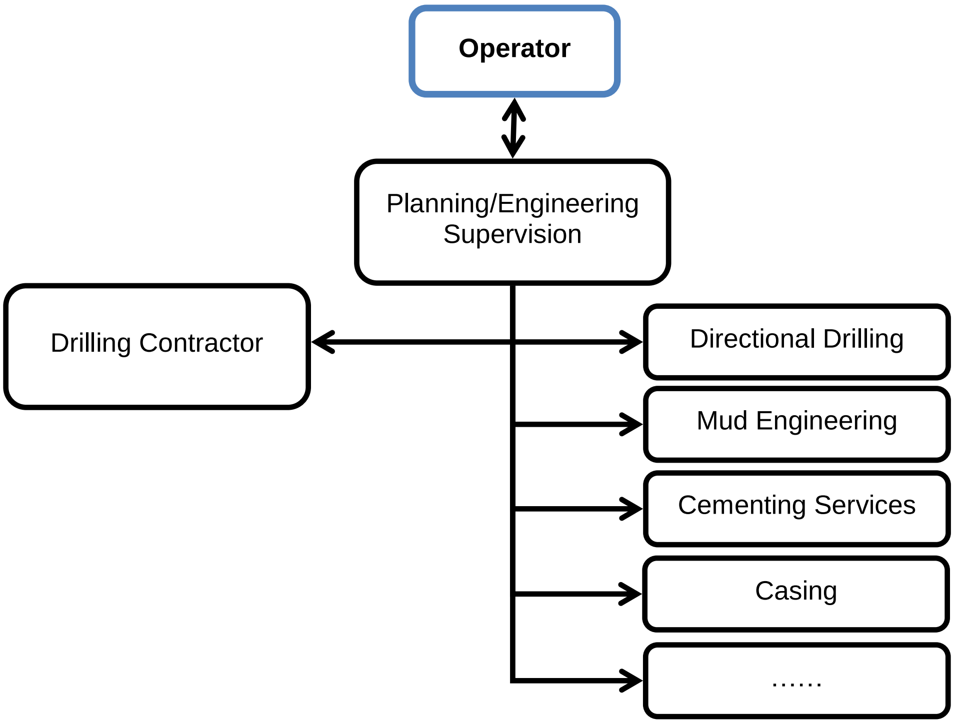

Figure 23 Project Management/Communication Structure under day rate without Main Contractor

DAY RATE (WITH MAIN CONTRACTOR) – SINGLE CONTRACTS

Under a day rate contract with a main contractor, the drilling contractor is responsible for all materials and delivery including sub-contractors (under a single contract). The main contractor will also typically include some supplementary costs in their pricing depending on the assumed risk and include a handling charge for subcontractors, which is normally between 10% and 15%. Apart from an increased cost for the well with the application of the handling charges, the individual subcontractors of the main contractor will often look to the Operator for supervision and coordination of the services provided by these subcontractors. Figure 26 and Figure 27 below provide an overview of the contract and project management structure for a day rate contract model with a main contractor. The Operator will still need to find and employ a planning/ supervisory team and will still 'own' the technical and geological risk.

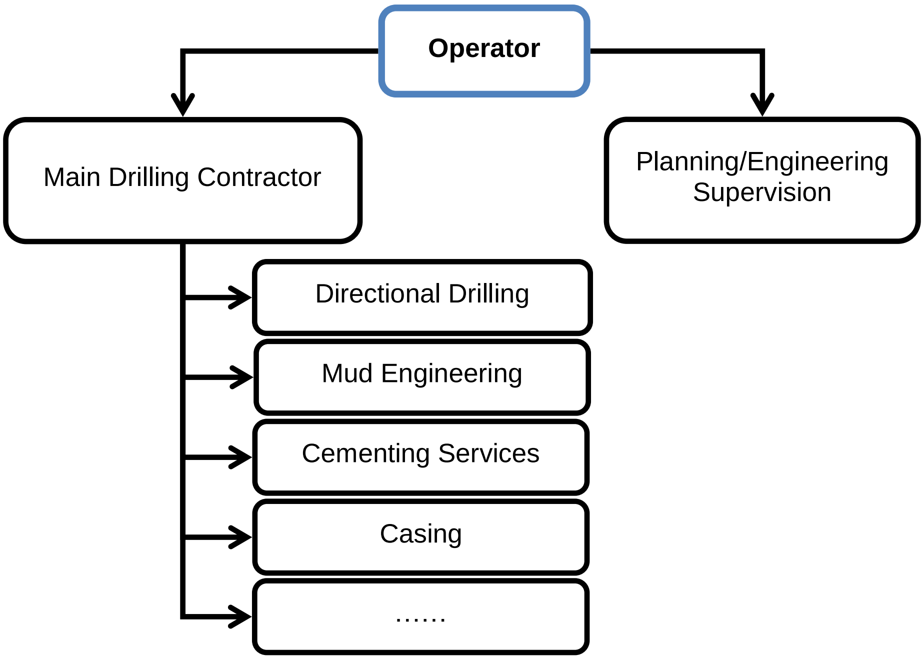

Figure 24 Contract Structure of Day Rate with Main Contractor

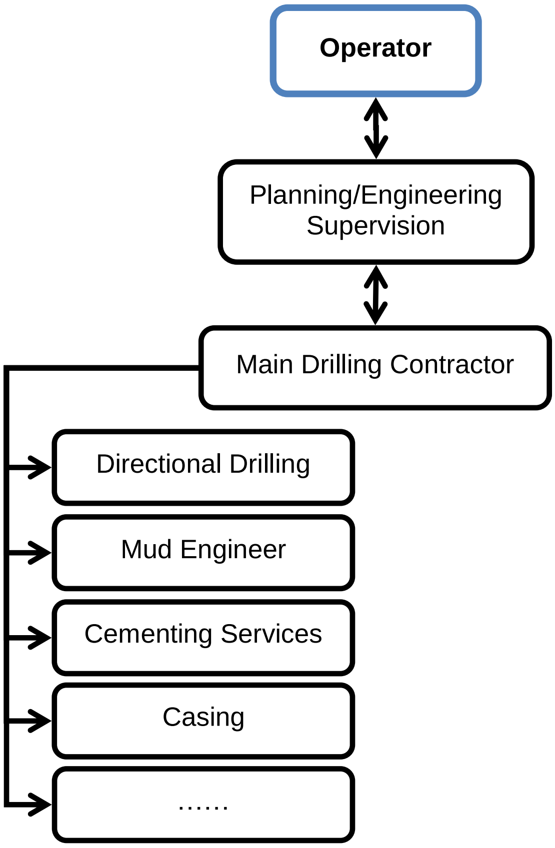

Figure 25 Project Management/Communication Structure under day rate with main contractor

SUMMARY

Both Turnkey and Day-Rate contractual structures offer potential benefits and problems for geothermal contractors wishing to develop projects in Scotland. A Turnkey approach can offer security of a fixed price but is likely to be expensive for complex, directional drilling in an essentially unknown geological environment. A day-rate contract on the other hand may suffer from cost over-runs that cannot be met from a small geothermal contractor and will require a highly experienced team to be hired by the geothermal contractor for the duration of the project along with experienced lawyers to handle the multiple contractual agreements. Prior to developing a project it is important that a geothermal developer understands how they intend to contractually manage a deep well in Scotland. If an appropriate contractual structure is not developed in advance of the drilling programme then a project may fail due to either litigation or, as is more common with geothermal projects, insufficient funds to complete the project due to cost over-runs falling on to the geothermal Operator.

For the single well system, we have designed the well to be as simple as possible to drill and install. Further, as the well does not require hire flow rates or operational pressures, the project is less prone to geological risk. It has always been our aim to roll out the DGSW systems in a similar way to water wells or piling projects under an Engineering Procurement Construction (EPC) contract. As such, we have been in discussion with a number of large scale contractors across Europe that are willing to operator under an EPC contract to deliver single vertical wells at a fixed cost. In particular, we have developed a relationship with Zublin (owned by Strabag (£20bn turnover)) who have experience of drilling and delivering projects across Europe. The EPC contracts have been adapted from those used by Arup in large scale construction projects throughout Europe and we believe that this approach offers the most sensible solution to the delivery of a deep geothermal single well at the AECC site for a fixed cost.

The following table (Table 5) provides an overview of the advantages and disadvantages of the different contract options discussed is this report.

	Turnkey / EPC	Day rate without Main Contractor	Day rate with Main Contractor
History	Principally Geothermal	Principally Oil & Gas	Principally Geothermal
Fixed delivery price	Yes	No	No
Technical Responsibility	With drilling contractor	With Operator	With Operator (except coordination)
Suitability to water wells/ standard construction	Yes	Yes but contractual complexity adds cost	Yes
Suitability to complex directional drilling in 'unknown' geological environments	No	Yes but needs strong supervisory and legal team supplied by Operator	Yes but needs strong supervisory team from Operator
Suitability to small contractor	Yes	No. Additional staffing required	No. Additional staffing required
Geological Risk	Borne by Operator	Borne by Operator	Borne by Operator
Technical Risk	Borne by drilling contractor	Borne by Operator	Borne by Operator (except coordination)
Cost over-run	Borne by drilling contractor	Borne by Operator	Borne by Operator (except coordination)

Table 5 Overview of advantages and disadvantages of the different contract options

INSURANCE

This section provides an overview of potential insurance mechanisms that can be used to insure the drilling phase of a geothermal project. There are four areas of a project that need to be considered:

- General Liability Insurance
- Exploration Insurance (Well Performance Risk Insurance)
- Construction All Risk Insurance (CAR)
- Lost In Hole Insurance (LiH)

GENERAL LIABILITY

The general liability policy concerns the legal liability in respect of property damage and personal injury to a 3rd party. The level of liability will depend on the local jurisdiction and legislation. In our experience on other single well projects, general liability coverage is typically available on a stand-alone basis for a project but can also be incorporated into the overall general liability policy of the Operator. A level of £10m (aggregate basis) is normally regarded as being a sufficient limit for a geothermal project. As a geothermal developer, GEL currently has this level of cover in place and it is a fairly standard insurance product in the UK.

It should be noted that if a geothermal project is located in a mining area, specific insurance requirements will probably need to be put in place. This should be discussed with the local mining authority where appropriate. In some cases mining law may provide a strict liability, where no negligence or willful intent needs to be proved for the project to be considered liable. Such strict liability would usually be excluded from common liability insurances. The pricing of a policy to cover this type of liability will vary substantially with different limits, scope of coverage and level of excess.

EXPLORATION INSURANCE (WELL PERFORMANCE RISK INSURANCE)

Exploration insurance covers the potential risk of the well not performing. In the context of a geothermal project the policy would cover an unsuccessful well in terms of the production flow rate, the temperature, the draw down in the well and thermal capacity.

In recent years, due to substantial losses, all insurers have stepped out of this market for low enthalpy geothermal projects in Western Europe. Across Europe, some Government backed policies are in place – most notably in France. There is no such Government backed risk insurance scheme in the UK. Therefore, in Scotland, an Operator will have to take on this risk with no insurance mechanism to re-coup costs. This is important when considering deep geothermal wells that require high flow rates in unproven geological formations. Without insurance mechanisms, we believe that private funding is unlikely ever to be involved in the drilling stages for these types of wells.

CONSTRUCTION ALL RISK INSURANCE

Construction All Risk Insurance typically covers the cost of any unforeseen property damage to the well during construction due to geological and technical risks. For example, well instability, stuck drill string (in an unsuccessful fishing attempt) and collapsed casings. The insurance should cover all expenses (e.g. labour, day rates of the rig, energy, cement, casings, etc.) incurred to bring the well back to the same standard as prior to the incident occurring.

Due to a large number of claims over the past decade across Europe, a significant number of commercial insurers have also stepped out of this market. As a result, underwriting capacity is limited depending on the location. Each project typically has to qualify for such coverage by providing evidence of a risk mitigating well design.

Where available, a typical excess for this type of insurance is in the range of £250,000 – £500,000 per loss. It is expected that the premium rate on the insured limit will be in the range of 4 – 7 % of the total cost of the well. The more expensive the well, the more expensive the insurance and Operators should bear this in mind when considering deep deviated wells in Scotland. The construction risk cover can be split into geological risks and technical risks:

GEOLOGICAL RISKS

The geological risks are defined as geological conditions, which have the potential to pose issues and therefore require additional remediation measures. These issues can result in, but are not limited to, delays, variations to design and damage to material and equipment. Such examples of covered issues are as follows:

- Total loss of drilling fluid resulting in complex control measures
- Differential sticking leading to (in the worst case) the drill string being stuck in hole

- Abnormal pressure formations leading to the collapse of the well and the requirement to drill a sidetrack well
- In well hydrocarbons requiring additional oil and gas control measures

TECHNICAL RISKS

The technical risks are defined as problems resulting from material, equipment and machinery issues, which typically require additional measures to be implemented, resulting in delays, variations to design and damage to equipment. Such examples of covered issues are as follows:

- Material failure due to mechanical and thermal stresses leading to pipe/liner rupture or breakage and drill rods becoming jammed in the well
- Damage to the well due to a service contractor
- Human error

Both geological risk and technical risk need to be very well defined and clear levels of responsibility allocated prior to awarding a drilling contract.

LOST IN HOLE INSURANCE

Lost in hole insurance covers the loss or damage of material and equipment underground and includes all associated material replacement costs.

If the drilling equipment is rented from a service company, the respective rental and lease contract will normally stipulate a liability to replace or indemnify lost and damaged subsurface equipment as new, irrespective of how worn the equipment was at the time that the incident occurred. This liability is typically transferred in its entirety through a rental contract from the drilling contractor (who rents the equipment) to the Operator.

The value of a new bottom hole assembly (BHA) consisting of a Rotary Steerable System (RSS), Measure while Drilling system (MWD) and other components can easily exceed £1 million. In the case of a LiH incident, fishing costs for attempts to retrieve the equipment back to the surface (which includes; specific fishing equipment, labour cost and travel expenses) will be incurred.

The excess for this type of policy is normally between 20-30% of the insured costs. Such coverage is generally still available in the market. The insurance premium is likely to vary between 5 - 15% of the total equipment cost although it will also depend on the complexity of the well design, the insured limits and the experience of the drilling contractor and company man.

SUMMARY

The table (table 6) below summarises the potential insurance mechanisms that will be available for deep geothermal projects in the UK. In addition an indication of the typical premium rate and excess is included.

Insurance Type	Coverage	Typical Premium Rate	Typical Deductibles
General Liability	• Third Party Property Damage • Third Party Liability	The premium and excess for general liability in the UK will be subject to the insurer and the relationship between the insurer and the Operator.	
Exploration	• Unsuccessful Well	Exploration risk insurance is not available in the UK whether through a commercial insurer of State backed scheme. If the well does not perform as expected then the Operator is financially at risk.	
Construction All Risk	• Unforeseen damage through: ○ Geological Risks ○ Technical Risks	4 - 7 % of total well costs per well	£250 000 - £500,000 depending on well construction and design
Lost in Hole	• Loss and Damage of material underground	5 – 15% of the max. drill string costs per well (£0.5m - £2m)	25 -30% of cost

Table 6 Summary of insurance mechanisms for a deep geothermal well

As discussed in the previous section on contracts, the deep geothermal single well has been designed to be a relatively straightforward drilling operation. As such, the well(s) will be drilled under EPC contracts. This allocates the Lost in Hole risk *and* the construction risk to the contractor. As Operator, we therefore do not need to add Construction Risk or Lost in Hole insurance costs to the project, resulting in further cost savings. For general liability as an Operator, we already have cover in place to £10m for the development of single vertical wells.

For other types of wells, particularly deviated deep wells, the construction risk insurance and lost in hole cover are likely to be passed to the Operator. This will increase the cost of the project due to the required insurance premiums.

COMMERCIAL POTENTIAL AND ROLL OUT

OVERALL MARKET, CONSTRAINTS AND STRATEGY

The overall commercial opportunity for the DGSW system is the market for heat supply in multiple apartment buildings, offices, leisure centres, anaerobic digestion plants and small heat networks associated with university buildings and schools. Key drivers for the DGSW are national and local targets for renewable energy along with long term security of heat price. The policy targets underpin the market assessment and are summarised in Figure 28.

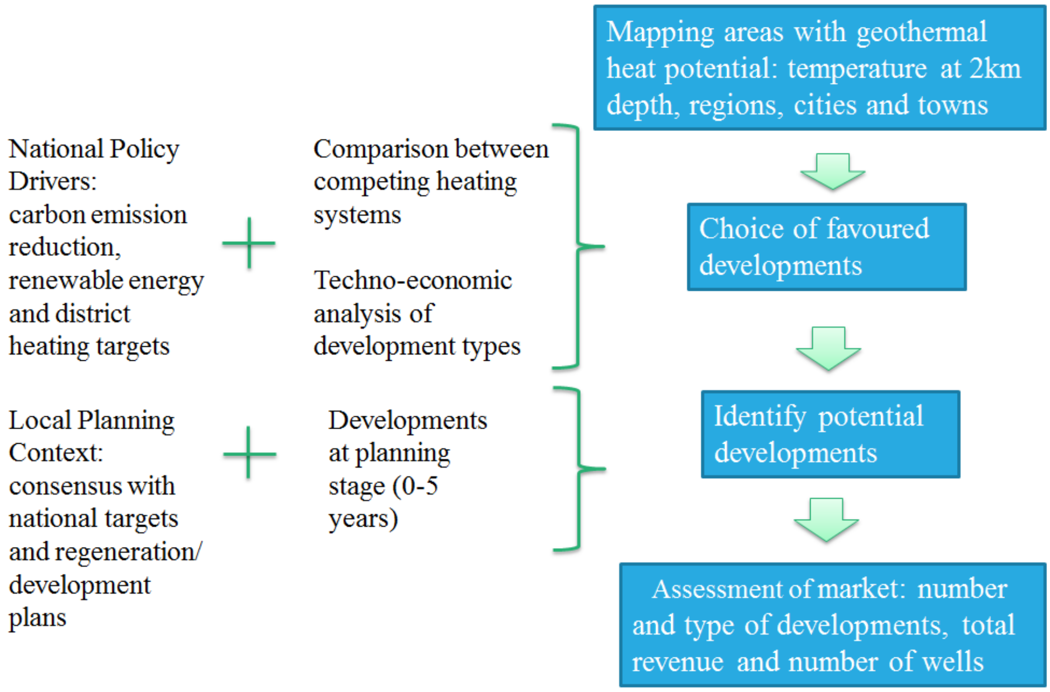

Figure 26 Methodology for the market study

POLICY DRIVERS

Table 7 below presents a summary of the main relevant national policies and regulations and an indication of the implications of each for the DGSW system.

Policy and Regulation	Scope	Measure	Implication for geothermal heat
Climate Change Act	UK	UK has set legally binding target to reduce GHG emissions by 80% by 2050 from 1990 levels.	Renewable energy will be key reducing UK GHG emissions. Geothermal heat is one of the most low carbon heat sources available.
Renewable Energy Target	UK	UK has set a target to generate 15% of energy supply from renewable sources.	Geothermal heat is a viable renewable energy source.
EU Energy Performance in Buildings Directive	European Union	Requires that all new public buildings are "nearly zero energy" by 2018 and all other new buildings meet that standard by 2020.	On-site renewable energy will be key to meeting that standard. Therefore DGH as a widely available renewable heat source will be very attractive to planners and developers in the lead up to these dates.
UK Government Plan for Growth	UK	Commitment to support "increased investment in low carbon technologies".	General statement of policy support.
The Future of Heating: A strategic framework for Low Carbon Heat in the UK	UK	Emphasis on the phasing out of gas supplied heat over time for domestic and non-domestic buildings, with DH networks covering urban areas and heat pumps serving lower density areas	Geothermal highlighted as a potential contributing technology to DH networks. Contribution potential is suggested to be minor.
Renewable Heat Incentive	UK	Payment for heat generation from renewable sources, set by the government and administered by Ofgem. Funding provided by the Treasury. Based on amount of heat generated, with average returns of 12% per annum. No size cap.	Deep geothermal heat is currently supported in the RHI through the deep geothermal tariff of circa 5p/kWh. Scottish Government focus on promoting the Renewable Heat Incentive.
Scottish Government - Heat Policy Statement	Scotland	Commitment to Decarbonisation of Heat in Scotland.	Scottish Government keen to see a self sustaining geothermal energy sector developed in Scotland.
Energy Performance Certificates	UK	EPCs display regulated the carbon emission per energy use in commercial and domestic buildings (EPCs) or whole building energy use in public sector buildings (DECs) . They enable owners and occupants to see the current energy performance of a building on a scale from A to G, and future potential if energy conservation measures were implemented.	Geothermal Heat would help buildings achieve a higher EPC rating.
Scottish Government -National Planning Framework	Scotland	Target of 11% of heat demand to be sourced from renewable sources by 2020. Therefore planning policy will be focussed on supporting low carbon, renewable heat projects.	Geothermal Heat projects should be supported by local authorities. Where current evidence bases underestimate the DGH potential, there may be a case for GEL to promote a revision to the evidence base to correct this error.
Aberdeen Local Development Plan	Scotland	Each local planning authority has its own Local Plan which is consistent with National Policy but also reflects local priorities, issues and opportunities for the built environment. The Aberdeen Local Development Plan R7 requires all new buildings to install low and zero carbon generating technology. Plan targets all new buildings to be carbon neutral by 2016. Geothermal Energy included in the eligible technologies to meet the requirements of the policy.	Geothermal Heat would be applicable to "carbon compliance" and "allowable solutions." Geothermal Heat could qualify as a renewable heat source for investment from carbon funds or directly by developers. Further work should be done to identify other leading local planning authorities, particularly in areas of high geothermal energy resource. Air quality policies will put pressure on combustion-based generation technologies such as gas and biomass. This will give DGH a further competitive edge in these locations. Geothermal can be an effective source of low carbon heat. Tightening standards will increase the market demand for such technologies.

Table 7 Policy drivers for the DGSW

CUSTOMER TYPES

The DGSW is suited to residential or commercial demand profiles such as blocks of flats (100 or more apartments), exhibition centres, warehouses, university campuses, greenhouses and leisure centres. Initial targets for the technology will include new developments with a strong interest in renewable and low carbon energy solutions to meet the greenhouse gas emissions requirements of Building Regulations.

ROUTE TO MARKET

For the DGSW to succeed, it will be important to have a demonstrator site in operation to both raise awareness of the technology and provide an opportunity for potential clients to see the system. Following on from the demonstrator site, the route to market is through the development of a heat utility company. We have recently launched the heat utility company (Geon Energy Ltd) to market and develop commercial opportunities. Shareholders of the company will include GEL and Arup.

OPERATIONS AND LOGISTICS

An important aspect of the DGSW is the scale of the heat network required for the system. With a peak output of between 400 and 600kW and annual operation of circa 2GWh (60% utilization), the system is well suited to small clusters of buildings or multiple apartments that are owned by a single entity (Council, University, Social Landlord, Leisure Centre operator etc.). The Heat Purchase Agreements and network ownership is therefore simpler than when dealing with a much larger network connected to multiple building and land owners. The standard approach we are taking to projects is a turnkey Heat Purchase Agreement and a Special Purpose Vehicle (SPV) heat company that is owned by the local community/ building owner and Geon Energy Ltd.

INTELECTUAL PROPERTY

There are currently no specific aspects of the DGSW that can be patented. This has been confirmed by DEHNS (Patent Attorneys at Law). During the development of the technology over the next decade there are likely to be some aspects of the DGSW/ building interface control system that can be patented and this is something that we will consider as projects develop. In the short term GEL and Arup will continue to develop in house 'know how' to maintain first mover advantage.

COMPETITIVE ANALYSIS

Compared to other forms of heat supply (both renewable and other), the DGSW can offer guaranteed, secure long-term energy costs. A comparison of existing heating technologies was undertaken in 2015 and the results are summarised in the graphics below. Figure 29 shows the competitive cost of the technology in the short and long term. Over a 20 year period (2015 to 2035) the levelised cost of a DGSW is expected to increase very little compared with the costs of producing heat from other technologies. This is due to the anticipated rise in the cost of fuel required for these alternative technologies.

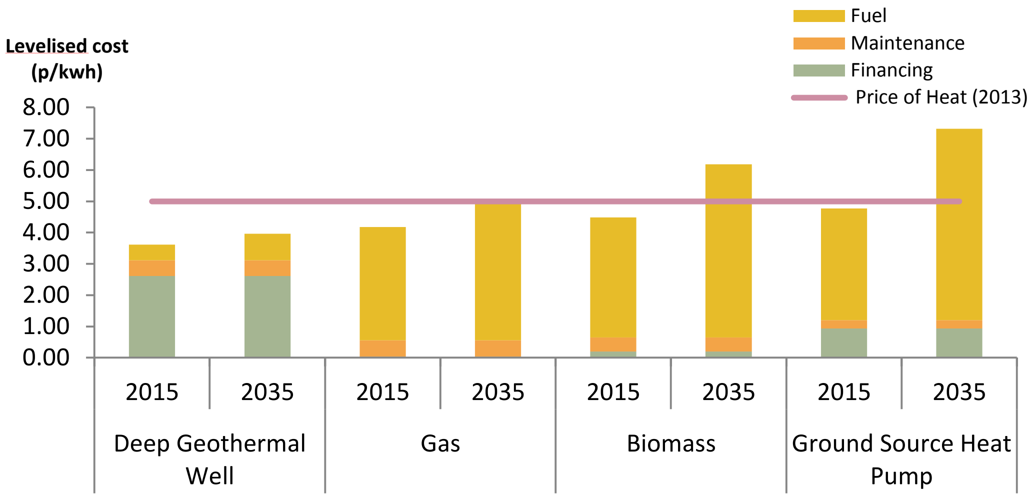

Figure 27 Comparison of levelised cost of heat (over 20 years) in 2015 and 2034 - alternative technologies

FINANCIAL MODELS

The proposed DGSW at the AECC is foremost a demonstrator system and will therefore be more expensive than a typical DGSW installation. This is due to the extended testing programme and the additional time required for the permitting associated with the first project of its kind in Scotland. For a typical DGSW in Scotland we have developed a detailed financial model for the installation and operation of the system over a 50 year period. The model has been summarised below in Table 8, Figure 30, Figure 31, Figure 32 and Figure 33. The results show that, provided the Renewable Heat Incentive remains in place, the return to investors is at an acceptable level for equity or debt funding. We already have a very strong appetite from investors for this type of technology once a demonstrator project has been proven in Scotland.

				Unit
Peak output from well			400	kW
Heat pump capacity			200	kW
Maximum Availability Factor			75%	%
Heat Tariff	Connection Charge	£	-	£
	Standing Charge	£	-	£/kW
	Heat Sale Price	£	0.0300	£/kWh
Total Revenue (Y1)		£	238,649	£
Total Capex		-£	1,580,000	£
Total Opex (Y1)		-£	48,897	£
Total Comodities (Y1)		-£	29,072	£
Project 40 Year NPV using 10% Discount Rate		£	10,700,069	£
Project IRR			18.81%	%

Table 8 Summary of project financials for a typical DGSW system with an annual utilisation rate of 75%

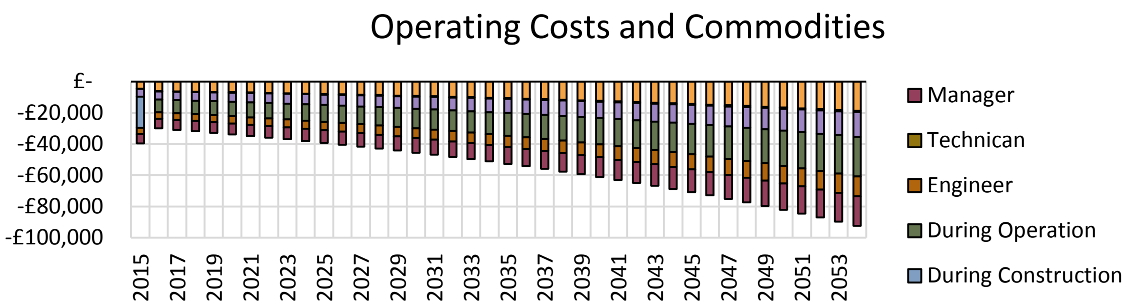

Figure 28 Operating costs for a typical DGSW system

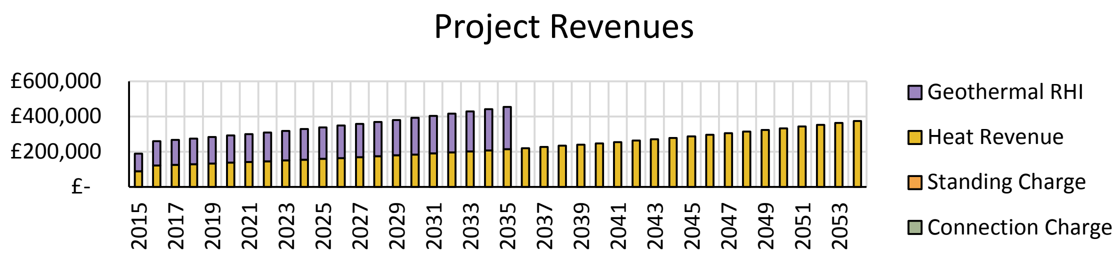

Figure 29 Project revenues for a typical DGSW system

Figure 30 Capital cost breakdown for a typical DGSW system

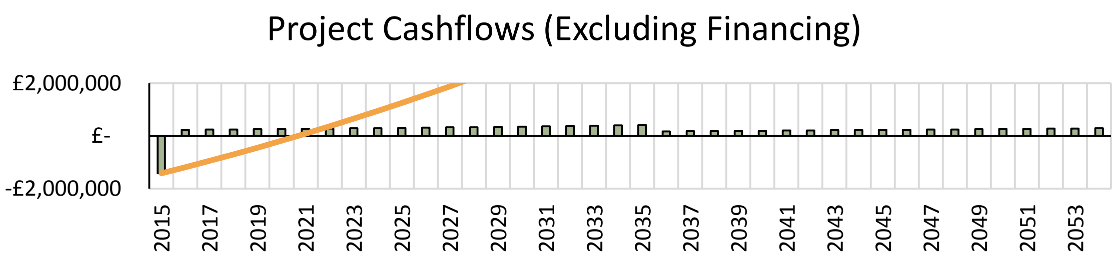

Figure 31 Cash flows for a typical DGSW installation

OIL AND GAS INDUSTRY CROSSOVER

Aberdeen is Europe's Oil & Gas capital and is home to an extensive oil and gas supply chain. The technical and commercial skills required to develop a deep geothermal project are very much aligned with those needed to develop an oil and gas exploration project and it is considered that the presence of these resources in Aberdeen offers a good opportunity for the crossover and transition of skills. We also highlight that in the current economic climate, with a declining price for crude oil and reduction in North Sea exploration budgets, that an opportunity for diversification and transfer of skills to geothermal exploration is now timely and opportune.

This section provides an outline on key areas where potential synergies exist and makes the case for Scotland to become a 'geothermal supply chain' leader.

EXISTING TECHNICAL & COMMERCIAL RESOURCES

ENGINEERING AND GEOLOGICAL SKILLS

We believe that the largest and most significant crossover potential between the oil & gas industry and low carbon deep geothermal energy is from the scientific and engineering disciplines aligned to oil & gas that are established in Aberdeen. The 2013 SKM Report on UK geothermal[50] highlighted that "*the crossover potential from oil and gas into geothermal offers a strong opportunity in fulfilling Scottish Enterprise's aim to encourage the transition of skills, technology and knowledge into low carbon energy sources*". Aberdeen is home to many specialist reservoir, petroleum and geological engineers within both operator and service companies who would be able to apply existing technical skills directly to the modelling, design and construction of deep geothermal wells. Geothermal technology could provide an additional employment opportunity for highly skilled engineers and scientists in the Aberdeen area. In addition, as geothermal development is so closely related to oil & gas exploration, the requirement for re-training the skill pool would be at a minimum compared to the level of investment needed to re-train for a different industry.

TECHNIQUES, EQUIPMENT & SUPPLY CHAIN

The supply chain for the delivery of any deep well is complex and specialised and requires both specialised personnel (reservoir modelling, geophysical testing, well design, well examiners, mud-loggers, drilling supervisors) and equipment (drilling rigs, casings, drilling consumables and cementing). Aberdeen already has all of these in place.

As part of the 2013 Atkins[51] review of geothermal energy a questionnaire was issued to a range of stakeholders (including the oil and gas industry) which included questions aligned to synergies between deep geothermal development and oil and gas technology developments. The responses to this questionnaire (from institutions including Durham University and Baker Hughes Reservoir Engineering) highlighted that there could be key contributions to deep geothermal development from existing technical areas including drilling, completions, water conditioning, fluid processing and pump systems in addition to the potential for 3D reservoir modelling technologies to be adapted for 3D modelling of thermal resources.

The presence of existing technical and commercial skills and equipment within the oil and gas industry in Aberdeen places Scotland in the position of becoming a leader and first mover to deliver technical expertise to

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[50] SKM - The Geothermal Opportunity for Scotland. May 2012
[51] Atkins – Deep Geothermal Review Study (DECC). October 2013

deep geothermal projects in the UK, Europe and beyond. The SKM study[3] stated that there are certain areas (particularly in technical and engineering) where there would be a potential for the development of a "*Scottish Geothermal Supply Chain*" where Scotland would be the main driver to this new industry on the back of existing skills from the oil and gas industry. The potential opportunities for supply chain crossover from the established oil and gas industry to a new deep geothermal industry has been acknowledged from discussions with specialist suppliers to UK offshore and onshore oilfield marketplace. Aberdeen's North Sea Field's Hartmann, who are international suppliers of valves and wellheads are keen to demonstrate how this potential new diversification opportunity can complement existing business. They have indicated a strong interest in exploring the potential diversification opportunity that a new industry could bring to its core business. Hartmann agree that a deep geothermal well located at the site of the new Aberdeen Exhibition and Conference Centre (AECC) "*would provide one of the best showcasing opportunities to the wider oil industry to permit further awareness and understanding of the crossover and supply chain opportunities to be developed further.*"

With an oil price of between $32 and $35 per barrel at the time of writing the report, we believe that there could not be a better time to develop a deep geothermal industry drawing on the existing skills and supply chains based in Aberdeen.

AECC AS A DEEP GEOTHERMAL DEMONSTRATOR SITE

The selection of the AECC as a deep geothermal demonstrator site will give the oil and gas industries already based in Aberdeen the greatest opportunity to observe and interact with geothermal technology and make the most of the synergies that exist and the crossover opportunities that are on offer. The Aberdeen Exhibition and Conference Centre (AECC) will host the Offshore Europe Conference & Exhibition, the Annual Oil & Gas Industry Conference and a host of Oil & Gas Industry trade events. Therefore, locating the first deep geothermal demonstrator at the AECC site offers not only the Aberdeen Oil & Gas Industry but the worldwide Oil & Gas industry the opportunity to view deep geothermal technology in action and understand the investment and supply chain opportunities that it offers.

LCA – LIFE CYCLE ASSESSMENT

INTRODUCTION

LCA is a technique used to assess the environmental impacts of a product or project. It typically includes the impacts of all project 'stages', from the extraction of raw materials, to manufacturing, distribution, use, maintenance and disposal. This is often referred to as 'cradle-to-grave'. Typically, an LCA will report on environmental impacts such as global warming potential (GHG emissions), acidification, photochemical ozone creation potential, eutrophication, resource depletion and human health impacts. The aim of the LCA conducted for this project was to compare emissions from installing and operating a deep geothermal single well (DGSW) for 50 years (the expected lifetime of the system) with a counterfactual case. In this instance the counterfactual case was 4 gas boilers (100kW each) for the same duration. It was assumed that under the DGSW case a 400kW boiler would be installed as backup and replaced every 10 years, but not used.

CONSTRUCTION CARBON

Emissions associated with the installation of a DGSW and associated plant equipment were calculated at 248 tonnes of carbon dioxide equivalents (tCO_2e). This includes embodied emission of the materials used, their transport to site, plant equipment fuel use and maintenance (i.e. the replacement of key items such as the water pump). The main contributor to construction emissions is the drilling of the 2km well and installation of the steel case, responsible for about 90% of construction emissions. The replacement of the steel case with glass-reinforced plastic (GRP) was considered, along with steel with a high-recycled content (59%). Figure 32 summarises construction related emissions and the saving that can be achieved (30%) by simply sourcing steel pipes with a high-recycled content.

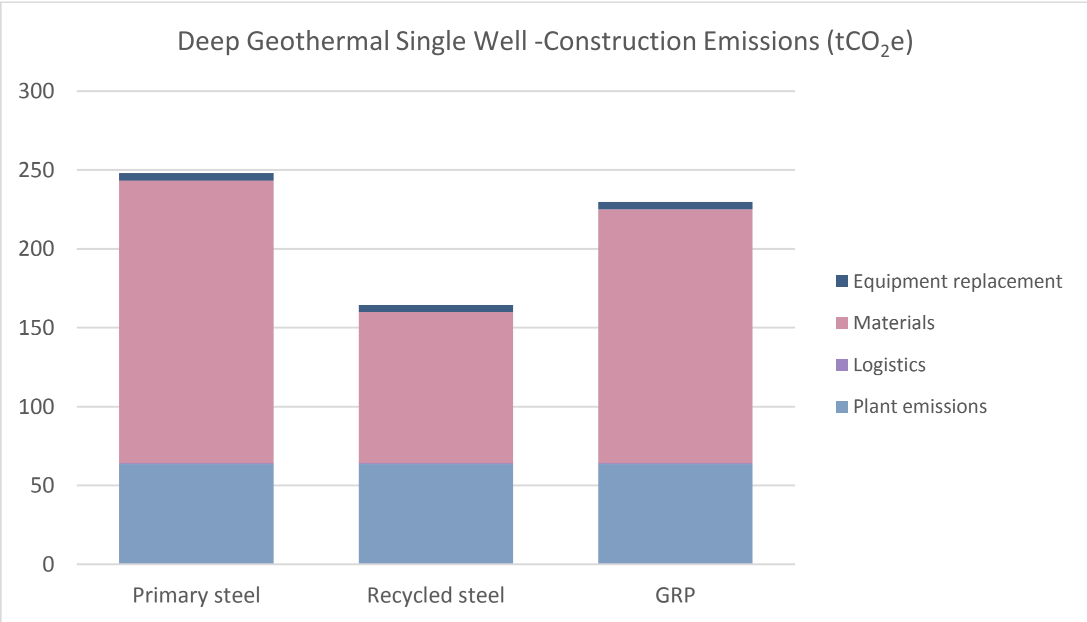


Figure 32 Deep geothermal well construction emissions – steel versus plastic pipe casing

The counterfactual case, whereby heating is provided through 4x100kW boilers, does not have any construction related emissions because the boiler system already exists today. However, the replacement of the boilers every 10 years does have a manufacturing and transport impact that was included. The impact is measured at just under 4 tCO_2e over 50 years.

OPERATIONAL CARBON

Heat supply from the DGSW has very low operational carbon emissions, approximately 35 tonnes per year (based on current grid carbon factors). This performance is 13 times better than gas fired boilers. This result was expected given the high efficiency of the deep geothermal system. The input electricity is used to circulate water to collect geothermal heat from the well base; as opposed to the gas boiler that is based on continuous combustion of a fossil fuel to produce heat. Both systems would require a plant room with controls that use minimal amounts of electricity. As a result, the carbon emissions for the gas boiler system are slightly lower under the decarbonising grid scenario.

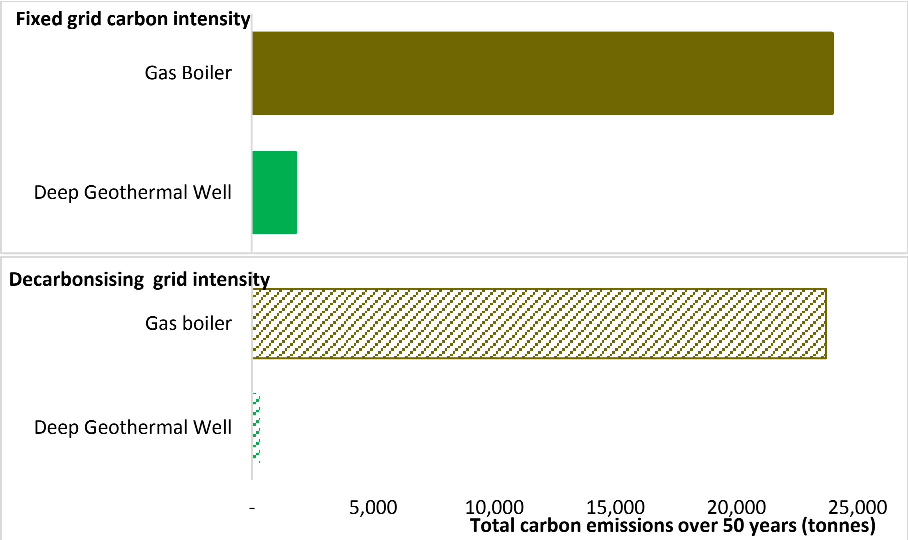


Figure 33 Carbon Performance of Heating Systems, under current grid intensity and future decarbonised grid scenarios

OVERALL LCA RESULTS – DGSW VS COUNTERFACTUAL

Over a period of 50 years, the DGSW is projected to emit a total of 2,008 tCO_2e (including construction, operation and maintenance emissions) whilst delivering an annual heat output of 1,800,000 kWh. This compares favourably to the gas boilers counterfactual whereby four 100kW boilers would deliver a similar heat output as the DGSW, but with lifecycle emissions over 50 years of 24,188 tCO_2e. In this instance, the DGSW is almost 12 times more efficient than the counterfactual gas boilers, achieving a saving of over 22,170 tCO_2e over 50 years[52]. Figure 36 plots the cumulative emissions of the two scenarios over 50 years. Construction, operational and maintenance emissions are included in the graph. Although the DGSW option has a higher carbon footprint initially (due to construction) compared to the gas boiler, once the DGSW is operating, the annual savings are significant enough to offset construction emissions in less than a year.

[52] Emissions here were modelled using a fixed UK grid factor.

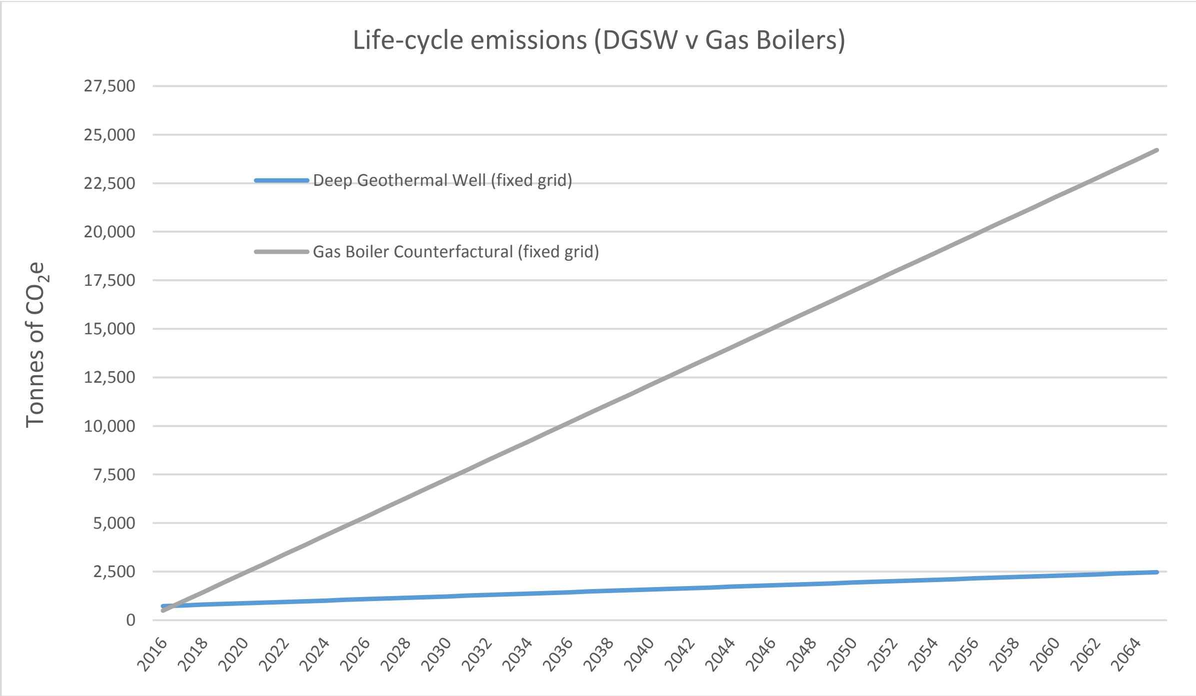


Figure 34 Life-cycle carbon emissions of a DGSW compared to the gas boilers counterfactual scenario

SENSITIVITY ANALYSIS AND UNCERTAINTIES

The life-cycle emissions of the DGSW and the gas boilers were modelled using both fixed and projected grid carbon intensity. Results show how the carbon savings achieved by the DGSW over the gas boilers are not particularly sensitive to switching from a fixed UK grid, to a decarbonised projection. A 3% increase was modelled, equivalent to 730 tCO_2e saved in addition by the DGSW over 50 years. This is a function of the small amount of energy the system draws off the power grid.

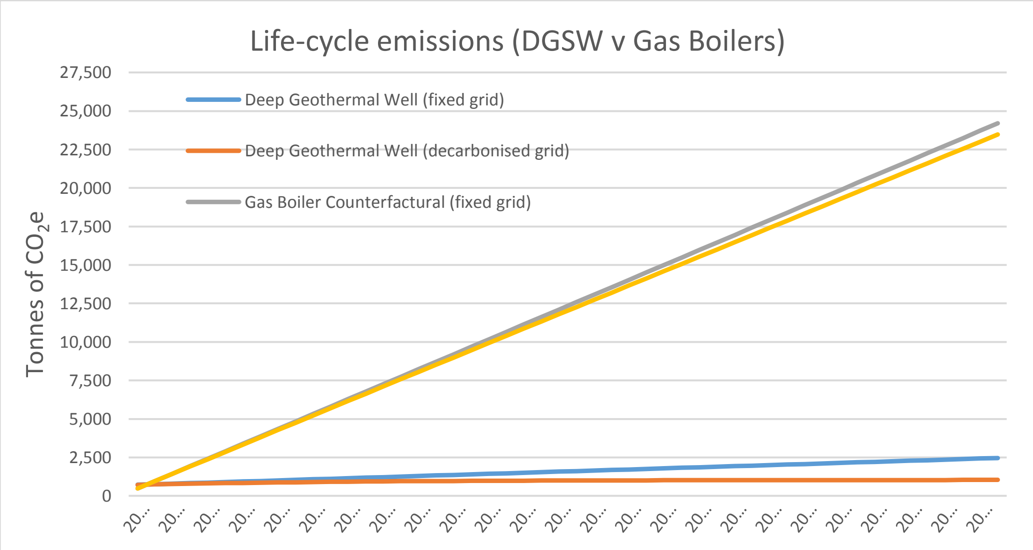


Figure 35 Life-cycle emissions of a DGSW compared to gas boilers, and their variance depending on UK grid projections

Figure 37 compares life-cycle emissions of the DGSW with gas boilers, and how these emissions may vary depending on fixed or decarbonised grid emissions. It is interesting to note how emissions associated with the DGSW are more sensitive to grid decarbonisation than the gas boilers. This is because the DGSW uses electricity to power the submersible pump, while the gas boilers' energy input is gas whose carbon content is fixed.

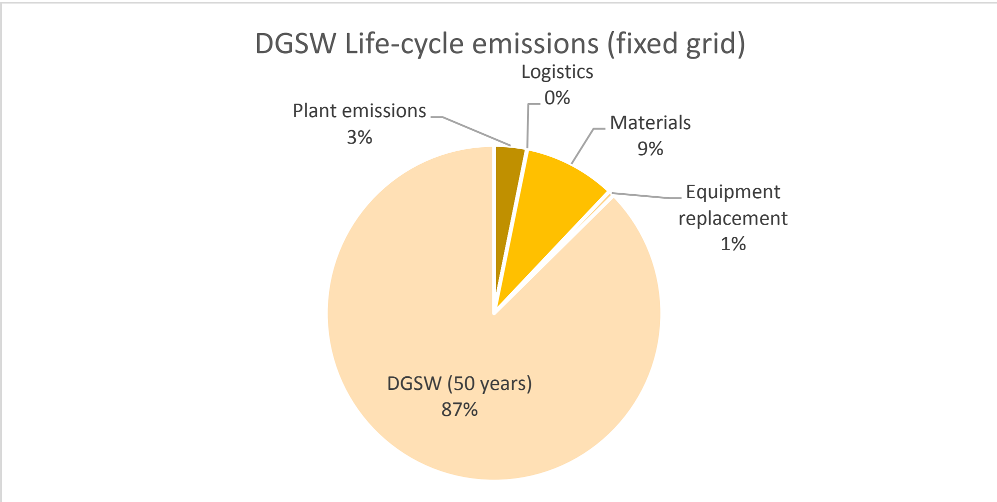


Figure 36 DGSW life-cycle emissions (fixed UK grid) by element and % contribution

Under the fixed UK grid scenario, the majority of emissions are from operating the DGSW (i.e. running the submersible pump, see Figure 38). This suggests that procuring efficient submersible water pumps is likely to have the most significant overall impact. If a decarbonised power grid projection is applied, the proportional mix of emissions changes (see Figure 39). Operational emissions are still the largest at 56%, but material and plant emissions also increase in significance. The largest contributor to material emissions is the steel casing, whilst the drilling rig dominates on-site construction emissions. Using recycled steel for the casing, or alternative materials such as GRP can reduce emissions. Currently the transport assumptions assume a 200km round trip for delivering all materials to site. Even a doubling in distance makes no significant difference to the overall life-cycle footprint. As a result, a sensitivity analysis of logistics was not undertaken.

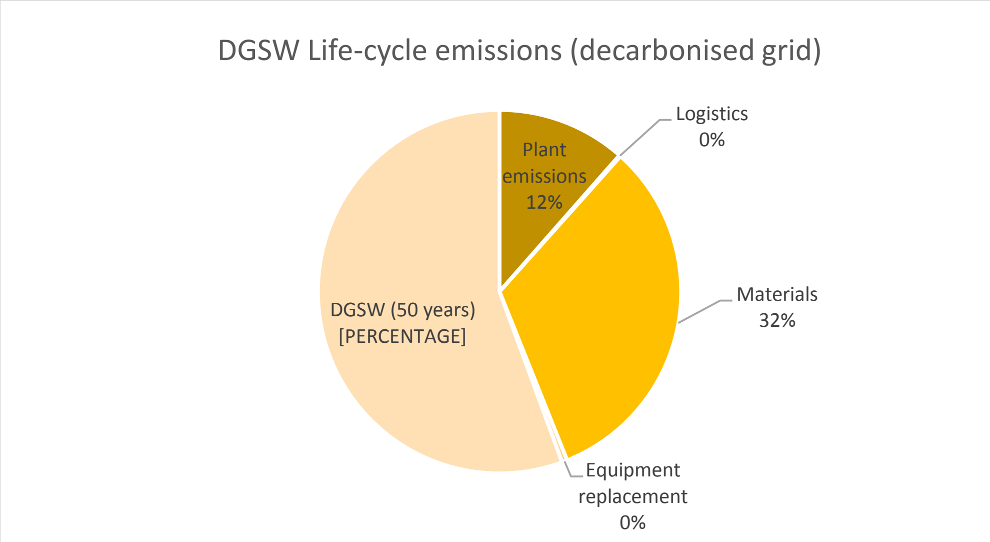


Figure 37 DGSW life-cycle emissions (decarbonised UK grid) by element and % contribution

LIFECYCLE COSTS

The lifecycle cost of the DGSW is characterised by low operating costs and high capital costs associated with drilling the well. This is the opposite of the gas boiler system for which the bulk of the lifecycle cost is associated with the fuel cost. The major advantage of the DGSW cost profile is that it is less vulnerable to price volatility in the energy market and the levelised cost of heat production is significantly below the market price. The geothermal solution could therefore offer price stability and savings to the customer and contribute to the UK's energy security. Figure 38 below provides the breakdown of lifecycle costs for both the DGSW and counterfactual. The capital costs associated with installation and upfront cost of equipment of the counterfactual were not included in the analysis because the demonstrator site currently has gas boilers installed. However, the gas boilers be replaced at least three times over 50 years and therefore their cost has been accounted for under equipment replacement costs. The annual fuel cost of the gas boiler is nearly 10 times that of the DGSW.

The analysis of the levelised cost of heat production over 50 years demonstrates the relative significance of capital, fuel and operational costs for each system. The overall result (Figure 38) demonstrates that the DGSW has a lower levelised cost of heat production than the gas boiler. This suggests that the DGSW could offer a price discount to the consumer, depending on the heat supply agreement and financing structure.

It can also be seen from Figure 40 that the levelised capital cost of the DGSW (which includes construction and equipment costs) supply is less than the fuel costs associated with the counterfactual. The operational costs of the gas boiler are therefore much more significant in driving up the lifecycle cost than that of the high capital cost of the well. It is important to note that these results are based on a 50-year heat supply, which, although consistent with the lifetime of a well, is currently beyond the norm for heat supply contracts that lie between 15 to 20 years and are most commonly specified for district heat networks.

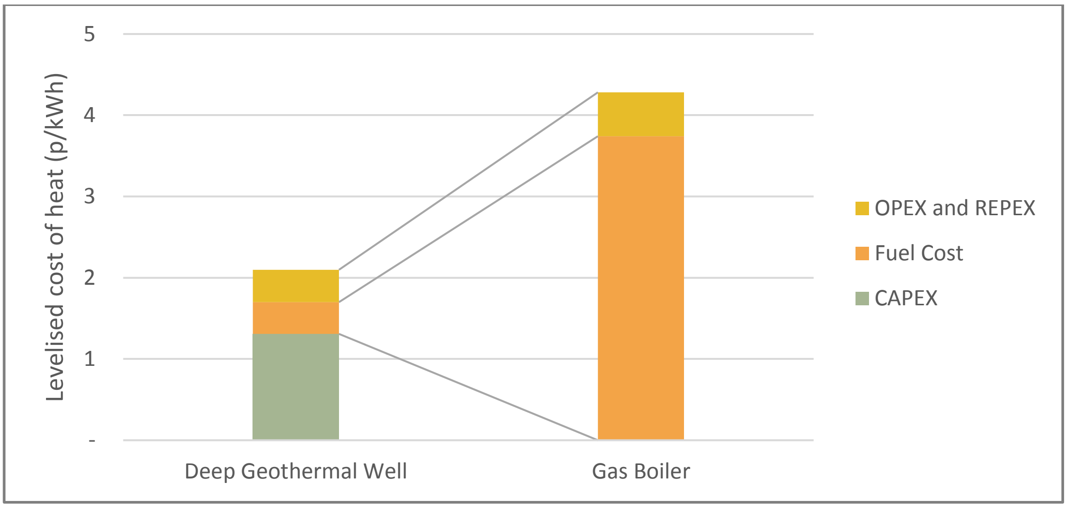


Figure 38 Levelised cost of heat over 50-year lifetime - comparison between deep geothermal well and gas boiler (counterfactual)

PROJECT DELIVERY AND COSTS

Due to previous recent project experience, the costs for the proposed project at the new AECC site are well constrained. Further, drilling and installation costs can be controlled under an EPC contract. For project delivery, our previous experience suggests that the following milestones/ work packages will be required:

1. Agreements, Contracts and Permitting (Planning and SEPA)
2. Drilling/ completion of the well and pipework installation
3. Testing and commissioning of the well /system
4. Integration with the system on site
5. Data analysis and reporting of the system operation

Each of these is explored in more detail in the following sections:

AGREEMENTS CONTRACTS AND PERMITTING

This first work package will cover all of the agreements, contracts and permitting for the project:

- **Legal Agreements**. Legal agreements regarding access to the site during the construction period and a long term lease of the area of the site where the well-head is located (normally a car parking space in size) will need to be drawn up and signed
- **Well design**. A site-specific detailed well design and methodology will be developed for HSE, SEPA and Planning Approval. This will also be used as a basis for the drilling tender documentation.
- **Permitting - SEPA**. All the required documentation will be prepared and submitted to SEPA for approval
- **Permitting - HSE**. Although not legally required for the project, all documentation will be submitted to HSE and an external well examiner appointed
- **Planning Permission**. The documentation outlined in previous sections will be prepared and submitted to Aberdeen Council. A public consultation day will also be held in a similar manner to that described above.
- **RHI**. If appropriate (dependent upon funding routes), we will also start the pre-accreditation process with Ofgem for the Renewable Heat Incentive. We have recently been through this process for a similar project in England.
- **Heat Purchase Agreement**. This will be drafted and agreed in principal between all parties
- **Drilling tender and drilling contract**. A tender process will be run for the appointment of a drilling contractor and other works for the project. The contractual arrangements and liabilities will need to be legally agreed between all parties
- **Insurances**. The legal responsibilities for the project will be allocated to all of the parties involved and sufficient insurance policies put in place.

DRILLING AND COMPLETION OF THE WELL, SYSTEM INSTALLATION

Once all of the required agreements, permits and contracts are in place, the next work package will be to drill the vertical well to the target depth and install the single well equipment. A draft programme for the drilling stage of the project has been included as part of this report. In total, we expect the drilling rig to be on site for approximately 40 days with the drilling itself taking 20 days. The whole process (including site preparation, mobilisation, fitting of the well equipment will take approximately 70 days.)

TESTING AND COMMISSIONING

Once the well has been drilled, we will conduct a suite of tests at the site in conjunction with St. Andrews University. The majority of these tests will involve the use of our Thermal Response Test rig that has been specifically designed and constructed for deep geothermal single well tests. Proposed tests include:

1. Wireline logging of the well
2. Temperature profiling
3. Geothermal water analysis
4. Bleed flow testing (hydraulic parameters of the well) – step draw down tests
5. Short and long term energy abstraction tests

This part of the project is estimated to take four months to complete.

INTEGRATION

Following the testing period, the system will be integrated into the plant room of the AD unit at the new AECC site. The integration consists of installing the heat exchanger, pipework connections, the pump control system and the interface with the Building Management System (BMS). The design, integration and commissioning of the system will be undertaken by M&E engineers at Arup.

During this stage of the project, the pipework will also be laid for the supply of return flow heat to the nearby residential dwellings and the individual heat pumps fitted in each unit.

OPERATION, ANALYSIS AND REPORTING

Once operational, the entire system will be monitored for performance over the first three years of operation. Monitoring will include:

1. Thermal performance of the well
2. Changes to the geo-fluid properties
3. Thermal delivery and efficiency
4. Maintenance requirements

The aim of the data analysis will be to complete the picture on how best to operate and manage DGSW systems under a variety of conditions. Due to the relative longevity of this work package, this has not been included in the overall project costs. It is expected that the long term monitoring of the project will be met from internal funds.

PROJECT COSTS

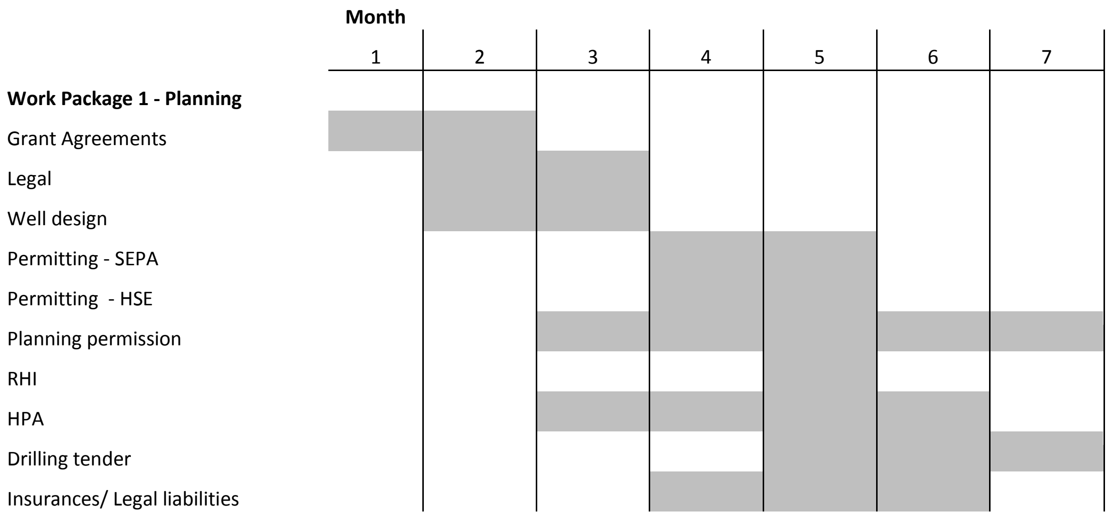
From experience of previous projects, we have developed good estimates of the costs required for each of the stages listed above.

These are summarised below and listed in detail against the proposed programme in the following sections.

			Date	Costs
Work Package	1	Agreements, Contracts and Permitting	Month 7	£147,440
Work Package	2	Completion of well/ System	Month 14	£1,713,150
Work Package	3	System testing	Month 21	£153,050
Work Package	4	Integration	Month 27	£279,000
Work Package	5	System operation report		Costs met internally
Total cost of project				**£2,292,640**

Table 9 Summary of milestones and associated costs for the project

OPERATIONAL COSTS – STAFFING



	1	2	3	4	5	6	7	TOTAL
Engineer	£4,480	£4,480	£5,040	£5,040	£5,040	£4,480	£4,480	£33,040
Senior Engineer		£6,000	£6,000	£6,000	£3,000	£1,000		£22,000
Director	£4,500	£4,500	£6,750	£9,000	£4,500	£4,500	£4,500	£38,250
Sub Consultants		£6,650	£13,300	£14,250	£11,400	£8,550		£54,150
Total	**£8,980**	**£21,630**	**£31,090**	**£34,290**	**£23,940**	**£18,530**	**£8,980**	**£147,440**

Work package 2 - Drilling and Installation	Month 8	9	10	11	12	13	14
Contract agreements	■	■					
Health and Safety		■	■				
Security			■				
Drilling and casing*				■	■	■	
Equipment installation							■

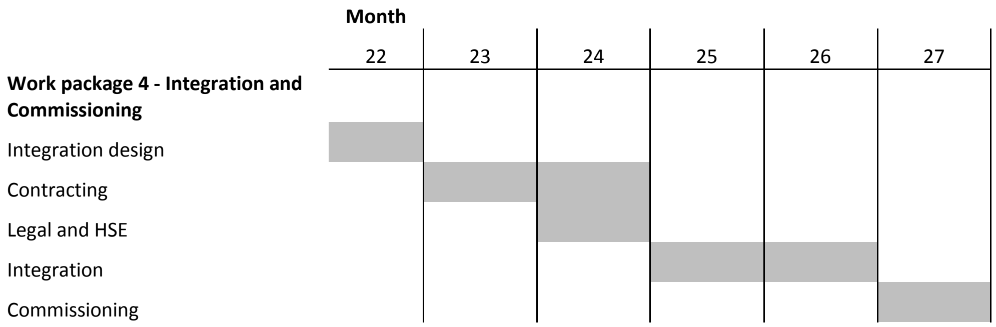
*See detailed programme

	8	9	10	11	12	13	14	TOTAL
Engineer	£4,480	£5,600	£5,600	£5,600	£2,240	£2,240	£2,240	£28,000
Senior Engineer		£6,000	£8,000	£10,000	£10,000	£10,000	£10,000	£54,000
Director	£4,500	£4,500	£6,750	£9,000	£9,000	£9,000	£4,500	£47,250
Sub Consultants	£5,700	£3,800		£28,500	£28,500	£28,500	£28,500	£123,500
Total	**£8,980**	**£21,630**	**£28,280**	**£29,230**	**£23,380**	**£18,530**	**£8,980**	**£252,750**

Work package 3 - Testing	Month 15	16	17	18	19	20	21
TRT movement and set-up	■	■					
Hydraulic testing			■	■			
Thermal testing				■			
Energy testing					■	■	
Commissioning							■

*See detailed programme

	15	16	17	18	19	20	21	TOTAL
Engineer	£5,040	£5,600	£5,600	£5,600	£5,600	£5,600	£3,360	£36,400
Senior Engineer	£7,000	£6,000	£8,000	£10,000	£10,000	£10,000	£2,000	£53,000
Director	£2,250	£2,250	£6,750	£9,000	£9,000	£9,000	£4,500	£42,750
Sub Consultants	£1,900	£1,900	£2,850	£2,850	£3,800	£3,800	£3,800	£20,900
Total	**£8,980**	**£21,630**	**£28,280**	**£29,230**	**£23,380**	**£18,530**	**£8,980**	**£153,050**



*See detailed programme

							TOTAL
Engineer	£5,040	£5,600	£5,600	£5,600	£5,600	£3,360	£30,800
Senior Engineer	£5,000	£6,000	£8,000	£10,000	£10,000	£4,000	£43,000
Director	£2,250	£2,250	£2,250	£4,500	£4,500	£3,000	£18,750
Sub Consultants	£3,800	£1,900	£2,850	£3,800	£3,800	£1,900	£18,050
Total	**£8,980**	**£21,630**	**£28,280**	**£29,230**	**£23,380**	**£18,530**	**£110,600**

CAPITAL EQUIPMENT AND TRAVEL

Equipment

Item	No.of items	Price per item (ex VAT)	Total
Polypropylene Pipe	1950	£30	£58,500
Pump	1	£10,000	£10,000
Riser	300	£20	£6,000
Thermistor string	1950	£4	£7,800
Surface pipework	Numerous	£1,000	£1,000
Steel weights	Numerous	£1,800	£1,800
Cable ties and sundries	Numerous	£4,500	£4,500
Connection pipework	Numerous	£800	£800
Bleed valve and isolation valves	4	£450	£1,800
Temp and flow sensors/ meters	Numerous	£2,200	£2,200
Pump control system	1	£3,800	£3,800
Bleed valve control system	1	£2,400	£2,400
Insulation	Numerous	£400	£400
Fittings	Numerous	£900	£900
Heat exchanger	1	£6,000	£6,000
Filtration unit	1	£2,500	£2,500
Equipment total			**£110,400**

Drilling

Detail	No.	Cost per item	Total
Drilling and completion of well*	1	£1,350,000	£1,350,000
Other total			**£1,350,000**

Integration

Detail	No.	Cost per item	Total
Equipment	1	£155,000	£155,000
Other total			**£155,000**

Total Capex	**£1,615,400**

* See detailed cost breakdown

Travel

Journey required and reason	No. of Journeys	Cost per Journey	Total
Site visits for negotiation	4	£200	£800
Site visits for M&E analysis	4	£200	£800
Site supervision during installation*	3	£3,000	£9,000
Site visits during testing*	2	£1,400	£2,800
Equipment total			**£13,400**

*Multiple nights at location @ £100 per night

DETAILED DRILLING COSTS

The total cost of drilling and casing the well at the AECC site is shown in Table 10. The costs for the drilling are based on a recent tender process for a similar project in England.

Section	Item	Unit	AFE		
			Quantity	Rate (£)	Total (£)
1. Drilling Operations					
	Site Preparation - (90m x 60m). Inclusive of fenced hoarded perimeter+timber matting and membrane liner Transport and erect hoarding around the site area c/w vehicle, pedestrian and emergency exit access gates • Excavate and install 3m deep x 2.1m ID concrete rings c/w concrete surround, concrete floor and 14" mousehole sleeve. • Lay "nappy" membrane over site and install sump for collection of run-off • Lay timber rig matting across site area	Sum	1	83,500	83,500
	Disassemble and remove from site all matting, membrane and hoarding on completion and install permanent fenced perimetre surrounding BH wellhead	Sum	1	46,200	46,200
	Pre-installed conductor (16" to circa 20m lump sum material incl.)	Sum	1	29,000	29,000
	Rig 16 Mobilisation & Demobilisation	Sum	2	79,500	110,000
	Rig 16 Drilling time @ 24 hours	Days	50	10,950	547,500
	Standby	Days			
	Fuel	Days	33	1,750	57,750
	Mud Engineer	Days	33	680	22,440
	Drilling fluids - 14 3/4" and 9 1/2" hole	Sum	1	55,167	55,167
	Drilling fluids - delivery	Load	5	700	3,500
	16" J-55 API 5CT Casing 75 ppf BTC	m	20	160	3,200
	10-3/4" J-55 API 5-CT Casing 51 ppf BTC	m	500	44	22,000
	7" J-55 API 5–CT Casing 23 ppf BTC	m	1,350	23	31,050
	Liner Hanger System - To enable suspension of 7" casing off of 10 3/4" casing from 350m	Ea	1	9,290	9,290
	16" J-55 threaded X 20-1/4" 2K flanged wellhead connector	Ea	1	1,550	1,550
	10 3/4" J-55 threaded X 13-5/8" 5K flanged wellhead connector	Ea	1	1,355	1,355
	Shipping and Transport of above casing and wellhead items	Allow	1	17,500	17,500
	Casing accessories - centralisers	Ea	200	30	6,000
	Casing accessories - stab in float shoes and guides - halliburton	Job	2	3,500	7,000
	Drill bits 14 3/4" hole - milltooth purchase	Allow	1	9,000	9,000
	Drill bits 9 1/2" hole - roller-cone purchase for shoe track	Allow	1	6,000	6,000
	Drill bits 9 1/2" hole - PDC	Allow	1	8,000	8,000
	Cementing 10 3/4" casing	Job	1	37,500	37,500
	Cementing 7" casing	Job	1	23,500	23,500
	Sub Total Drilling Operations				**1,138,002**
2. Logging + testing					
	Wireline logging suite (1 run @ TD - temperature and caliper))	Allow	1	10,000	10,000
	Sub Total Logging etc				
3. Water & Waste					
	Waste disposal based on low to medium solids content and WAC test acceptance				
	Liquid wasted disposal - waste mud	Tonne	440	58	25,520
	Transport	Load	20	700	14,000
	Solid waste disposal - cuttings	Tonne	193	40	7,720
	Transport	Skip	24	350	8,400
	Produced water with zero hydrocarbons and within pH4-10.5	Tonne	TBA		
	Water Supply	Allow	TBA		
	Sub Total W & W				**55,640**
4. Rentals etc	Site offices/ welfare for mud engineer, toilet block, office and canteen for crew and 3rd part personnel	Days	35	150	5,250
	Site offices/ welfare for supervisory staff				
	Incidental rental item i.e. tower lights, minidigger, pump etc./ Other procurement	Days	50	150	7,500
	Rental of 21 1/4" annular diverter for 14 3/4" section				
	2 7/8" EUE cementing string - 2000m + inspection charges upon completion	Sum	1	15,500	15,500
	Centrifuge Hire	Days	38	250	9,500
	Centrifuge Hire - mob/demob and commissioning/ decommissioning	Sum	1	4,000	4,000
	Shaker Screens and Pump Parts	Days	33	350	11,550
	Estimated repair costs for all downhole tubulars DC's & stabs	Allow	1	20,000	20,000
	Sub Total Rentals etc				**73,300**
5. Other	Security services	Allow	TBA		
	Dedicated supervisor	Allow	TBA		
	Independent well design	Allow	TBA		
	External well design examination	Allow	TBA		
	Sub Total Other				**0**
	GRAND TOTAL				**1,266,942**
	Contingency	%	10		126,694
	Total with contingency				**1,393,636**

Table 10 Detailed expected drilling costs

RESOURCE MANAGEMENT

Geothermal Engineering Ltd (GEL) will be responsible for running and managing the project but will work closely with Arup and the University of St. Andrews on project delivery. The company has extensive experience of geothermal projects (heat and power) in the UK and abroad. The company has recently installed and tested the DGSW technology in an existing deep well as part of the DECC funded Energy Entrepreneurs Fund and delivered the project on time and on budget. The team for this project will consist of the following staff members:

Entity	Name	Role
GEL		
	Ryan Law	Chief geologist and project director
	David Bridgland	Chief engineer and financial controller
	Peter Ledingham	On site operations and Health and Safety
	Adrian Jackson	On site management and installation of equipment
Arup		
	Mike Collins	Well design, project management and client liaison
	David Brown	Planning and permitting
	Barry Austin	M&E building integration
	Stephen Cook	Heat network contracts
Eversheds LLP		
	Stephen Hill	Legal

GEL has worked with all of these parties on a number of previous parties and already has a strong working relationship in place.

PROJECT PROGRAMME

The individual milestones and associated costs for the project can be found in previous sections. The following two figures (Figure 41 and 42) show the overall programme for the project and a detailed analysis of the drilling and casing programme.

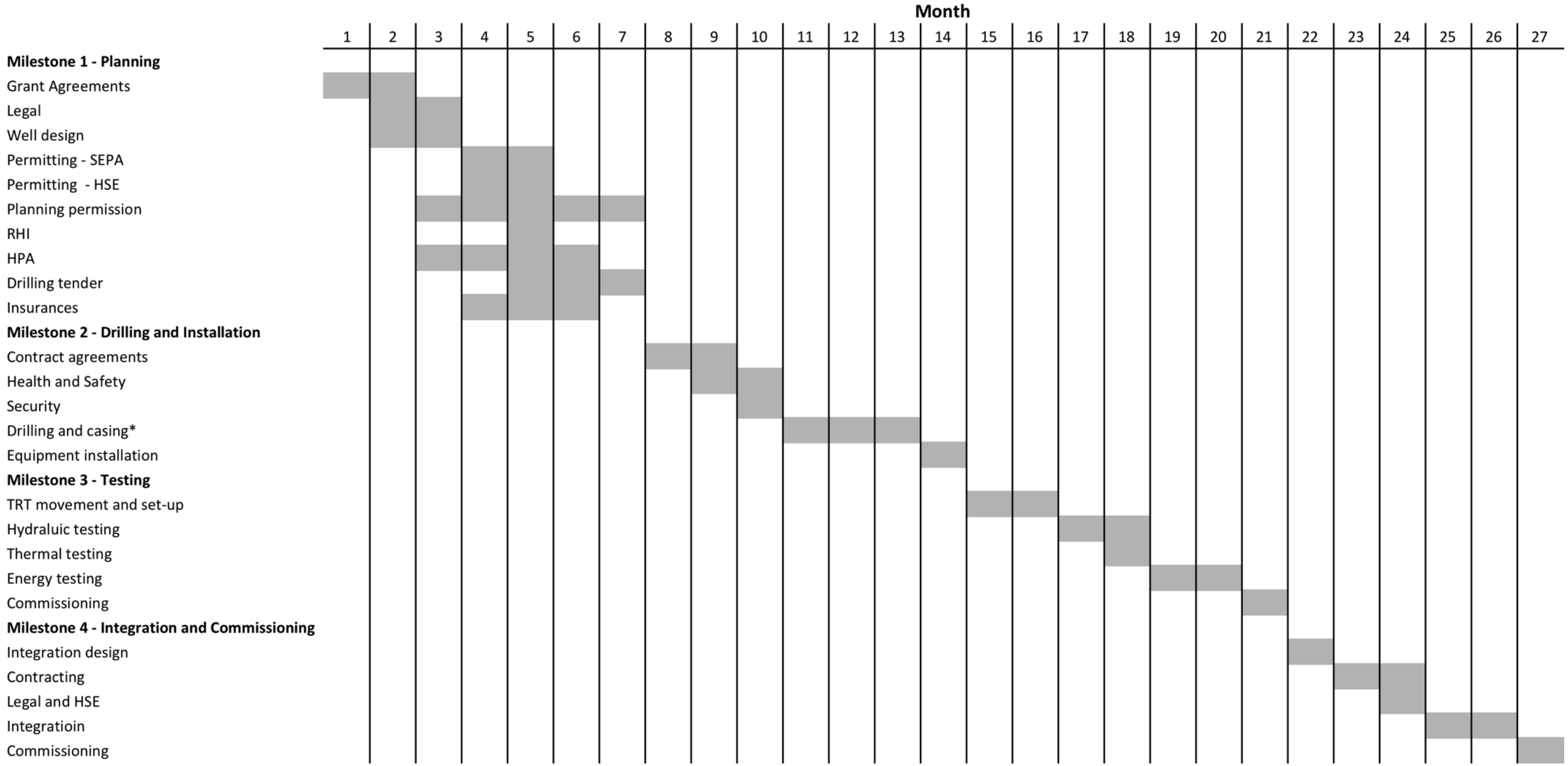


Figure 39 AECC DGSW Project programme

PROJECT TITLE:

Aberdeen Exhibition and Conference Centre

1 x 2000m Deep Geothermal Borehole Project

ID	Task Name	Predecessors	Duration
1	**GEL - Deep Geothermal Borehole**		**53 days**
2	**Site Setup Phase**		**10 days**
3	Temporarily remove any in situ buildings and other items on drilling site and install heras "anti-climb" perimetre fence around site c/w 2 x vehicular and 1 x pedestrian access gates and site signage as appropriate		2 days
4	Mobilise plant, excavate and install 3 x 2.1m ID concrete rings and mousehole sleeve. Concrete in place	3	3 days
5	Install impermuable "nappy" geotextile membrane layer and timber rig matting lain over rig footprint area (1400 sq. m) c/w access ramps and installation of sump to collect surface water run-off.	4	5 days
6	**Drilling Phase**		**48 days**
7	**Pre-Installed - Conductor Section - Auger Rig (12 hr)**		**5 days**
8	Mobilise to site and setup Auger Drilling Rig		1 day
9	Drill and install 20" conductor casing using water well rig to +/- 20m	8	3 days
10	Rig down Auger Rig and demobilise from site	9	1 day
11	**Main Hole - Rig 16 (24 hr)**		**43 days**
12	Mobilise to site Rig 16 and setup ready to spud	10	5 days
13	Install wellhead connector and annular BOP. Function and pressure test. Fill mud tanks	12	0.5 days
14	Make-up 14 3/4" BHA. RIH, tag and drill out cement	13	0.5 days
15	Drill 14 3/4" diametre to section TD of +/- 500m. Combined ROP = 2.5 m/h	14	8 days
16	POOH and lay down 17 1/2" BHA. Rig up cement equipment	15	0.5 days
17	Run 10 3/4" casing to +/- 500 m and cement grout in place	16	1 day
18	WOC	17	1 day
19	Make-up 9 1/2" BHA, RIH, tag cement and drill out shoe track	18	0.5 days
20	Circulate and condition mud. Perform FIT	19	0.5 days
21	Drill 9 1/2" section from +/- 500m to +/- 2000m. Combined ROP = 4 m/hr	20	16 days
22	POOH BHA and lay down	21	0.5 days
23	RIH 9 1/2" cleanout bit and perform wiper trip	22	0.5 days
24	Rig-up wireline logging equipment	23	0.5 days
25	Run basic logging suite comprising temperature and calliper	24	0.5 days
26	Install liner hanger at 350m and RIH 1350m of 7" liner	25	1.5 days
27	Clean mud tanks	26	1 day
28	Rig down all equipment and demob from site	27	5 days
29	**Site Dismantling Phase**		**5 days**
30	Install temporary fencing surrounding cellar location for clients after use. Lift timber matting and membrane and remove from site. Empty surface run-off sump and infill. Take down hoarding perimeter and remove from site	28	5 days

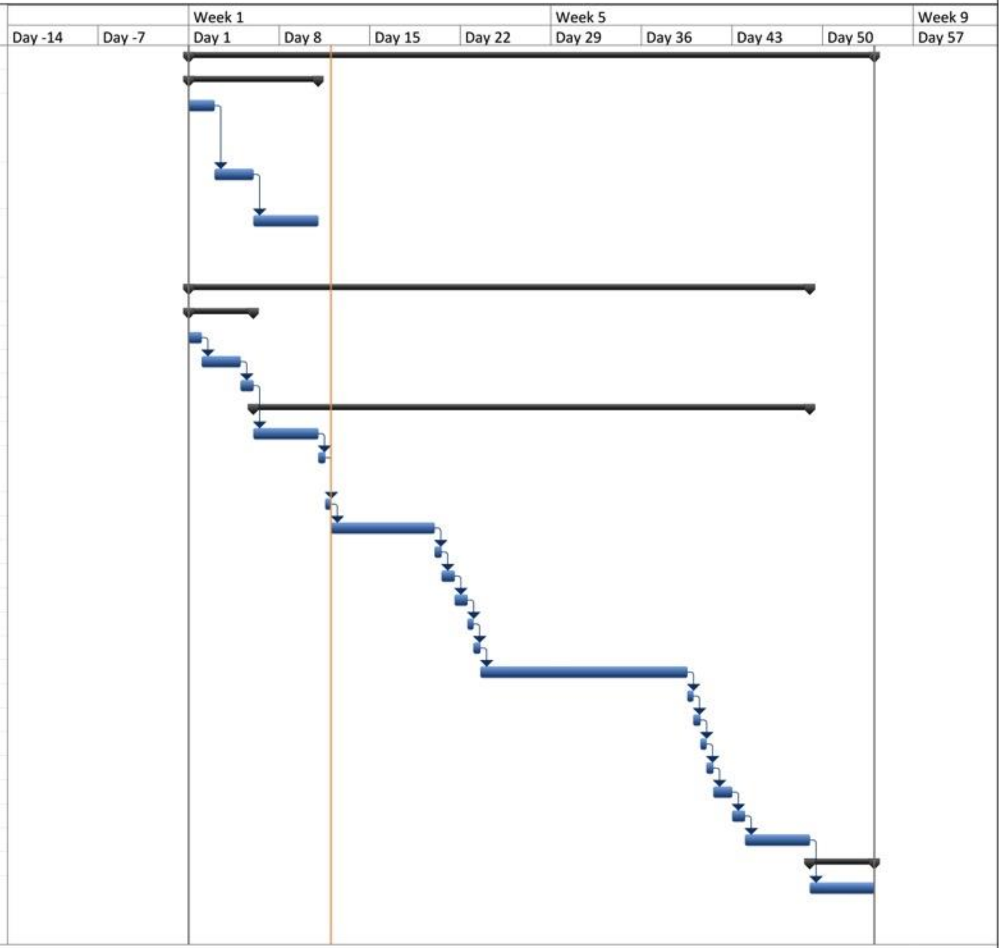


Figure 40 **Estimated drilling programme**

PROJECT RISKS

Assumptions, dependencies and risks related to the project are shown in the tables below. We have split these into reputational, operational and technical.

Risk	Risk rating					Risk effect			Mitigation	Risk owner	Action date
	Likelihood	Impact	Risk rating	Control	Significance	Time	Cost	Environmental			
Reputational											
Accident during construction	2	5	10	1	10				H&S site management procedures must be in place and followed.	GEL	Complete at end of installation
Pollution incident	1	5	5	1	5				Analyse water quality within the borehole at the site. Ensure no potential pollutants are used during the trial.	GEL	Complete at end of installation
Funding											
Funding not received or raised or withheld for the project	3	5	15	4	60				Ensure regular liaison with funding bodies. Complete milestones/ work packages as stated. Ensure project is on schedule and delivers. Manage delivery schedules and budgets.	GEL	Complete at end of project
Consents											
Permissions not received	1	5	5	2	10				Constructive dialogue must be maintained with the Local Authority during all phases of the project	GEL	Complete once written consent received
SEPA permission not given	1	5	5	2	10				Maintain good contact with SEPA. Clearly state all planned procedures.	GEL	Complete once written consent received
Financial											
Failure to calculate costs correctly	3	4	12	1	12				Regular cost review (internal and contractors). Regular update of internal spreadsheets. Cost control through EPC contracts	GEL	Complete at end of project
Project costs exceeded	3	5	15	1	15				Regular cost review and comparison with overall budget	GEL	Complete at end of project
Changes to financial programme	3	4	12	1	12				Regular notification of potential changes to funders and review of cost items	GEL	Complete at end of project
Operational											
Equipment not delivered on time	4	5	20	3	60				Order long lead items with sufficient time. Over estimate delivery times. Chase suppliers during delivery period. Purchase items upfront if required to ensure on time delivery. Order from established companies.	GEL	Complete at end of installation and integration
Equipment installation problems	2	4	8	2	16				Ensure highly qualified technical staff on site at all times during fitting of equipment. Daily review of installation procedures and potential for improvement.	GEL	Complete at end of installation and integration
Equipment installation failure	1	5	5	2	10				Order equipment already tested from established manufacturers. Insurance cover must be sufficient in case of total failure	GEL	Complete at end of project

Risk	Likelihood	Impact	Risk rating	Control	Significance	Time	Cost	Environmental	Mitigation	Risk owner	Action date
	Risk rating					**Risk effect**					
Equipment non-functional	2	4	8	2	16				Equipment must be chosen from established suppliers and correctly specified. Where possible, 'off the shelf' items should be chosen. Ensure staff with sufficient technical expertise on site during system testing.	GEL	Complete at end of project
Integration with existing plant room not successful	2	5	10	2	20				Good knowledge of the plant room must be developed prior to Phase II. Use experienced M&E personnel	GEL	Complete at end of integration
System does not perform as expected	3	4	12	2	24				Ensure all data properly recorded. Evaluate problems internally and externally as required.	GEL	Complete at end of project
Staffing											
Sufficiently trained staff not available	3	5	15	2	30				Fix dates within programme. Ensure dialogue with any consultants established early on in the project	GEL	Complete at end of installation
Failure to recruit staff for installation	3	5	15	2	30				Secure funding as per any schedule. Ensure dialogue with any consultants established early on in the project	GEL	Complete at end of installation
Technical											
Electrofusion joint breaks during installation	1	5	5	1	5				Electrofusion jointing is stinger than the pipework material itself provided jointing procedure is correctly followed. All jointing must therefore be undertaken in a clean, dry environment by highly qualified and experienced staff. If there is any doubt about a joint it must be cut out to ensure structural integrity in the pipe. During installation, the joint should not be over stressed at any point during lifting.		
Polypropylene pipe cannot be installed to target depth	2	5	10	2	20				Well must be tested for obstructions prior to installation. PP pipe must be properly weighted at regular intervals to overcome any potential for buoyancy.		
Thermistor string damaged	2	2	4	1	4				One member of staff must always be responsible for monitoring the string during installation. String should be tied at regular intervals to PP pipe. String must never exceed maximum bending angle.		
Thermistor string comes loose	1	2	2	1	2				String must be regularly and securely tied to PP pipe during installation		
Polypropylene pipe slips out of clamp on well head	1	5	5	1	5				Tightening of clamp must always be undertaken by two members of staff (one to tighten, one to observe)		
Polypropylene pipe slips out of clamp during lifting	1	2	2	1	2				Tightening of clamp must always be undertaken by two members of staff (one to tighten, one to observe)		
Well pump and cable cannot be installed to target depth	3	1	3	1	3				PP pipe must be inspected to ensure no obstructions prior to installation. Riser and cable must be sufficiently taught during installation		
Well pump functions for limited period of time	2	5	10	2	20				All data from the pump and the TRT unit should be recorded during installation to locate whether problem is electrical or physical. If the problem is not electrical then the pump should be removed and inspected. It is therefore important that the crane is present on site until the pump has been shown to function		

Risk	Risk rating					Risk effect			Mitigation	Risk owner	Action date
	Likelihood	Impact	Risk rating	Control	Significance	Time	Cost	Environmental			
Well pump does not produce at required rate	2	5	10	3	30				Pump must be correctly sized for expected drawdown in well at required flow rate/ bleed flow. Ensure pump is installed at the correct depth in the well. Check that pump is correctly wired for three phase supply (wrong direction will cause reduced flow)		
Filtration unit blocked	2	4	8	3	24				Regular inspection of filters. Analyse water first produced from the well.		
Differential expansion between PP pipe and thermistor string causes tension in the string	4	3	12	1	12				Ensure that there is sufficient play in the thermistor string at the surface to account for differential expansion		
Oxygenation of well water during re-injection	2	2	4	2	8				Water returned to the well will be oxygenated which may cause bio-fouling at the top of the well. This should not affect the abstracted water which is coming from >1800m in the well. Again, regular inspection of the heat exchanger and filters should be undertaken as a precautionary measure		
Heat exchanger encounters problems with well water	1	3	3	1	3				The heat exchanger should be manufactured for the expected type of well water. The heat exchanger should be monitored at regular intervals for any alterations in pressure drop.		
Communication failure between BMS system control and DGSW	1	2	2	1	2				Ensure only experienced staff manage the integration of the DGSW with the control system		
System suffers unexplained failure during testing	2	5	10	3	30				The system may suffer catastrophic failure for a reason not expected or foreseen. To try to prevent this, data from the well must be constantly monitored and any alteration in performance of the heat exchanger, well pump or delivery temperature needs to be reported.		

CONCLUSIONS AND NEXT STEPS

This report has evaluated the technical and economic potential to drill, install and connect a Deep Geothermal Single Well (DGSW) system to supply heat to both the Anaerobic Digestion unit and surrounding residential units at the new site for the Aberdeen Exhibition and Conference Centre (AECC). The DGSW will consist of a single, vertical well drilled to a depth of approximately 2km within the granite beneath the site.

A geological review and a conservative thermal modelling exercise has concluded that the site is located in an area where temperatures will be within the required operational range for the DGSW. In addition, the site is not considered to be in a location where deep waters would contain significant levels of contaminants or harmful gases such as Radon.

The DGSW has been designed to function in almost any geological environment and therefore represents a very low risk method of capitalising on the deep geothermal heat present in Scotland. The system has also been demonstrated to have a very high efficiency that means that the lifetime carbon savings are substantial when compared with a conventional gas boiler. The carbon emissions associated with drilling and casing the well is offset within the first year of operation making this a very attractive technology to contribute to the decarbonisation of Scotland's heat supply.

The new AECC site represents an excellent opportunity to host a deep geothermal heat demonstration project and to showcase how deep geothermal heat can be harnessed for a number of uses (both commercial and domestic). The site has good access for both drilling the well and any ongoing maintenance required during the system operation.

Drilling and developing a DGSW at the AECC site will provide:

- A low risk method of proving the deep geothermal heat resource
- A high profile showcase site for deep geothermal heat (commercial and domestic), including an exhibition and education centre
- Benefits to the immediate local community via a low temperature network
- Much needed temperature and geological data from deep on-shore drilling
- A system that does not require fracking or "stimulation". This will be important for ensuring that the local community is on side.
- The best opportunity for demonstrating the commercial opportunity of deep geothermal heat.

The project programme and associated costs have been listed in the financial section of this report. The total programme will be approximately 27 months and the next stage of the project will be to achieve all of the necessary permits for the site and contractual arrangements to drill the well and delivery the system. The total cost of the project will be £2.3M. The costs of the project can be well constrained as we have existing data from similar projects that we are currently in the process of developing in the UK. Further, because these wells will be drilled under Engineering Procurement Construction contracts that we have developed on previous projects, the overall costs can be well constrained. This will not be the case for geothermal projects with directional doublet wells.

The project represents a very exciting opportunity to prove that deep geothermal heat is a low risk, viable source of renewable low carbon heat in Scotland. It also offers the unique opportunity to use the international AECC venue to educate the community on the subsurface in general and the use of deep geothermal heat and to showcase the technology to the oil and gas industry and commercial investors from around the world.

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