Scotland’s Geothermal Supply Chain Analysis and Global Market Opportunities Study

Final Report

Scottish Enterprise

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Executive Summary

It is widely recognised that Scotland's oil and gas industry is world leading, but that it needs to adapt and diversify as we address climate change and reduce greenhouse gas emissions. Geothermal energy sector development, for both power generation and heating, is one potential area of opportunity which has been identified, with previous work indicating that it offers scope for diversification for drilling, sub surface modelling, corrosion mitigation and data analytics expertise developed in the oil and gas sector.

This study, therefore, assesses the geothermal market opportunities for selected oil and gas sector capability, with a specific focus on geothermal power generation, geothermal heat production, including district heating networks, and geothermal opportunities in abandoned mines.

There are several different types of geothermal resource. In this study, we have focussed on the most prominent current type, namely conventional geothermal, and two emerging types that are expected to demonstrate high growth in near future, engineered geothermal systems and closed loop geothermal systems. The study also explores opportunities within mine water geothermal.

- Conventional geothermal refers to natural formation of a hydrothermal resource where water is heated in the Earth and has become trapped in porous and fractured rocks beneath a layer of relatively impermeable rock. The exploitation of conventional geothermal has focused, to date, on sites where the resource is relatively easy to access, and the resource temperature is high enough for the operation to be commercially viable.
- The term engineered or enhanced geothermal systems (EGS) refers to the practice of creating a geothermal reservoir in hot rock by injecting water into wells to create fractures. The process has generated considerable interest as EGS can be applied wherever there is hot rock at accessible depths, which is nearly everywhere on the planet.
- Closed-loop geothermal (CLG) systems use sealed wells to circulate a heat transport fluid through the subsurface. This eliminates the need for geothermal fluid flow from the reservoir formation to the surface. There is no fluid exchange with the reservoir or surrounding area – the geothermal fluid is not circulated
- Abandoned mines can be used as a geothermal energy resource, using the natural heat contained in the mine water. Heat can be extracted from the mine water by use of water-source heat pumps. As this is a low temperature resource, the heat could be used directly to either support a large heat customer (single building such as school or tower block), district heating or to feed into industrial applications, such as heating greenhouses.

The global geothermal energy market is already established, with significant growth demonstrated over the last 10 years. This market is expected to grow significantly over the period to 2050. Global geothermal electricity generation, including engineered geothermal systems, is expected to grow by a factor of ten over the period from 2020 to 2050. In terms of the European market, it is estimated that Europe has an installed geothermal electricity capacity of 3.5 GWe in 2020, distributed over 139 power plants.

A wide range of geothermal temperatures can be used for heating, in applications such as space and district heating, spa and swimming pool heating, greenhouse and aquaculture ponds heating and for industrial processes. The global geothermal direct use market is predicted to grow by a factor of six over the period from 2020 to 2050. There were 350 geothermal district heating systems in operation in Europe in 2020 and a further 232 were in various stages of development

The largest geographic electricity generation markets are the USA, Indonesia, the Philippines and Turkey, with all these countries also having large portfolios of planned projects. The USA had an installed geothermal energy capacity of 3,676 MW in 2019, with 2,133 MW installed in Indonesia, 1,918 MW in the Philippines and 1,526 MW in Turkey, with Indonesia is set to become the leading geothermal market.

Almost 220 oil and gas supply chain companies that have capabilities that offer the potential for diversification into the geothermal supply chain were identified. These can be segmented as follows:

- Well engineering 131 companies
- Sub-surface modelling 15 companies
- Corrosion mitigation 25 companies
- Data 46 companies

Further, a significant number of these companies have demonstrated the potential to innovate and / or to access international markets

The geothermal sector has a number of technical challenges to address as it continues to grow and maximise output. These are listed in the following figure:

Conventional Geothermal	Deep Geothermal	Engineered Geothermal Systems	Closed Loops Geothermal Systems	Abandoned Mines
Well structure failure	New drilling techniques	Directional Drilling	Complex and accurate directional drilling	Modelling to understand heat depletion
Corrosion and scaling	New tools	Real-time data and long-term monitoring	Use of advanced fluids	Corrosion and fouling
High flow rates	Improved modelling and simulation	Transfer of knowledge from shale gas fracking	Advanced turbines	
Failure of pumps	Minimise maintenance			
Integrated design	Improved sensors			

Geographic geothermal markets are dependent on the specific geological conditions in different regions. As a result, similar geological conditions are being exploited in similar ways in different regions, leading to similar challenges and, thus, opportunities in these regions.

These challenges offer opportunities for new entrants to the sector. Sixteen specific areas of opportunity for Scottish oil and gas companies were identified through analysis of these technical challenges. The opportunities that are considered to be most attractive are:

- Improved well structure (casing, tubulars, cementing etc.)
- Corrosion and scaling prevention and maintenance
- Sensing technology to support measurement while drilling (high temp and pressure)
- Sensing technology to support long term monitoring
- Sensing technology to support flow assurance
- Improved subsurface and surface physical modelling to support reservoir characterisation and prediction of production

Based on the work carried out in this study it is recommended that:

- Scottish oil and gas companies are encouraged to pursue geothermal market opportunities

- Priority markets for Scotland, based on current activities, future growth and need for new technologies are Turkey, Indonesia, the USA and Germany. These should be initial target markets for development.
- More in-depth analysis of specific opportunities is carried out to support Scottish companies pursue them
- Access to a database of developing and new geothermal projects and contracts is established to identify forthcoming opportunities for Scottish companies
- Market access mechanisms, through a range of linkages, including diversified oil and gas companies and national renewable energy organisations, are developed

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1 Introduction

1.1 Context

It is widely recognised that Scotland's oil and gas industry is world leading, but that it needs to adapt and diversify as we address climate change and reduce greenhouse gas emissions. Further, Scotland's aim to achieve net zero emissions by 2045 imposes the need for the sector to change quickly. Already a number of oil and gas companies have successfully transitioned into renewable energy activities, particularly offshore wind, and it is expected that national and regional renewable energy hubs and the energy transition zone being developed in Aberdeen[1] will further support diversification of oil and gas companies. However, it is important that additional market opportunities are identified to optimise future opportunities for oil and gas companies.

The geothermal energy market is one area of opportunity which has been identified. Here, expertise developed in drilling, sub surface modelling, corrosion mitigation and data analytics could be transferred between the oil and gas and geothermal sectors. Geothermal energy is exploited for both power generation and heating, with many plants already established. For example, there were 3.5GWe of installed geothermal electricity capacity and 350 geothermal district heating systems in operation in Europe in 2020[2] and 15.6GWe of installed geothermal electricity capacity worldwide[3]. Further, it is predicted that the global geothermal energy market will increase from a value of $44 billion in 2020 to $50 billion in 2027[4], and continue to grow thereafter.

This study, therefore, assesses the geothermal market opportunities for selected oil and gas sector capability, with a specific focus on geothermal power generation, geothermal heat production, including district heating networks, and geothermal opportunities of heat recovery from abandoned mines using heat pumps.

1.2 Research Objectives

The specific objectives of this study were:

- Identify and map Scotland's oil and gas supply chain capability in drilling, sub surface modelling, corrosion mitigation and data analytics that could exploit geothermal opportunities
- Identify and characterise geothermal market opportunities that are attractive for Scotland's oil and gas supply chain capability
- Recommend attractive market opportunities for diversification

1.3 Research Method

Our methodology for this study consisted of:

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1 https://www.opportunitynortheast.com/energy and https://www.gov.scot/news/delivering-an-energy-transformation/

2 European Geothermal Energy Council Geothermal Market Report 2020, see https://www.egec.org/wp-content/uploads/2021/06/MR20_KF_Final.pdf

3 https://www.thinkgeoenergy.com/thinkgeoenergys-top-10-geothermal-countries-2020-installed-power-generation-capacity-mwe/

4 Geothermal Energy Market Size by Technology, Industry Analysis Report, Country Outlook, Covid-19 Impact Analysis Competitive Market Share & Forecast, 2021 – 2027, Global Market Insights, May 2021

- Desk based analysis of databases and websites to identify relevant Scottish companies with capability in drilling, sub surface modelling, corrosion mitigation and data analytics.
  A number of databases were reviewed to identify these companies, namely:
  - Scottish Industry Directories subsea engineering database[5]
  - Scottish Industry Directories low carbon heat database[6]
  - The Energy Industries Council's EICSupplyMap, a database of over 3,000 UK-located energy sector companies, from which Scottish Enterprise downloaded lists of potentially relevant companies
  - The database developed in the Glasgow Geothermal Energy Research Field Site (GGERFS) Company Demand Analysis
  - Scottish Enterprise "big data" databases

  These sources also enabled inclusion of companies already operating in the geothermal sector. This analysis is presented in Section 2, below, with the database of companies that was developed provided in a separate Excel document.
- An initial review of the geothermal market, based on a combination of desk research and stakeholder interviews, as summarised in Section 3, below
- A more detailed analysis of the market and identification of attractive opportunities for Scotland, as detailed in Section 4
- Preparation of opportunity profiles for the most attractive opportunities and these are included in Section 5 of this report

The work was carried out in October and November 2021.

5 https://subsea.directories.scot/
6 https://heat.directories.scot/

2 Supply Chain Analysis

2.1 Supply Chain Taxonomy

A taxonomy for classifying companies within the four specified areas of capability (drilling, sub surface modelling, corrosion mitigation and data services) was developed, as follows:

Well engineering	Subsurface modelling	Data	Corrosion
Well drilling		Data collection	Surface engineering e.g. coatings/galvanising
Well testing		Data communication	Corrosion control e.g. cathodic protection/inhibitors
Drilling and completion engineering		Data management	Corrosion monitoring e.g. NDT, etc.
Support services		Data analytics	
Well components / systems		Visualisation	

Figure 1: Supply Chain Taxonomy

2.2 Database Structure

The database structure developed to collate details of relevant companies has the following key fields:

rec.id	Company Name	Company Registration Number	Oil & Gas Sector?	Primary Classification	Secondary Classification													Description
					Well drilling	Well testing	Drilling and completion engineering	Support services	Well components / systems	Data collection	Data communication	Data management	Data analytics	Visualisation	Surface engineering eg coatings/galvanising	Corrosion control eg cathodic protection/inhibitors	Corrosion monitoring eg NDT etc	

Figure 2: Structure of Company Database

The database is structured so that companies can be listed by either primary or secondary category, enabling easy listing of companies in specific supply chain categories.

In addition, company address and website details were collated.

2.3 Database of Supply Chain Companies

An initial review of the databases highlighted in our methodology section identified around 1,200 companies. Of these, 820 companies appeared only in one specific sub-category in the EICSupplyMap (Wells and Reservoirs). Upon analysis, the companies in this category were only loosely connected with the four specified areas of capability. In order to generate a focused database, therefore, companies that appeared only in this category were excluded from further analysis. This gave a preliminary database of 335 companies. Analysis of the capabilities and activities of these companies identified 220 companies within the supply chain categories defined above. These are listed in the accompanying document (Scottish Enterprise Geothermal Supply Chain Companies.xlsx). The segmentation of these companies by supply chain category can be presented as follows:

Well drilling	Well testing	Drilling and completion engineering	Support services	Well components / systems	Data collection	Data communication	Data management	Data analytics	Visualisation	Surface engineering eg coatings/galvanising	Corrosion control eg cathodic protection/inhibitors	Corrosion monitoring eg NDT etc
31	9	17	33	66	26	12	17	13	4	7	3	18

Figure 3: Number of Companies by Supply Chain Category

Note: Some companies were allocated to more than one category due to the range of capabilities offered, so the sum of companies in each category is greater than the total of 220.

Within these categories we have numerous types of companies ranging from subsidiaries of global players, such as Schlumberger, to local SMEs and university spin-out and start-ups, e.g. Orbit Earth.

These can be presented in simplified supply chains as follows, highlighting the supply chain segments with most companies represented.

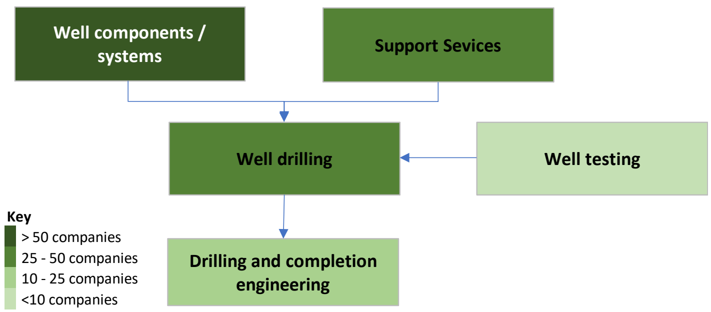

Figure 4: Simplified Supply Chain – Well Engineering

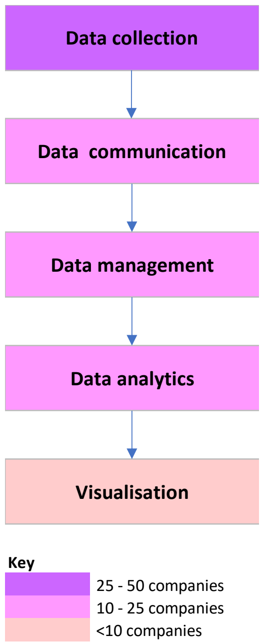

Figure 5: Simplified Supply Chain – Data Analytics

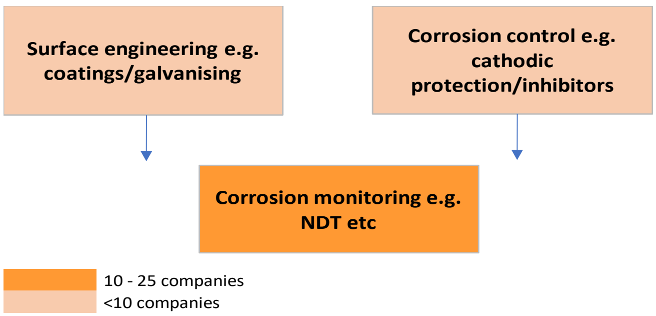

Figure 6: Simplified Supply Chain - Corrosion

Note: The subsurface modelling supply chain was not segmented into more precise categories.

This analysis shows that the largest numbers of companies are present in:

- Well components and systems, which includes a wide range of companies supply products ranging from basic materials to complex engineered systems
- Well drilling
- Well engineering support services
- Data collection

This supply chain database was used for matching attractive geothermal market opportunities with Scottish capability, as described in Section 4, below.

3 Market Assessment

3.1 Geothermal Resource and Types

3.1.1 Conventional Geothermal Resources

Conventional geothermal refers to natural formation of a hydrothermal resource where water is heated in the Earth and has become trapped in porous and fractured rocks beneath a layer of relatively impermeable rock. Sometimes hot water and/or steam can reach the surface, creating hot springs or geysers but, in most cases, it remains trapped and accessible only by drilling. Typically, such resources are associated with volcanic settings, limited to those with active or young volcanoes.

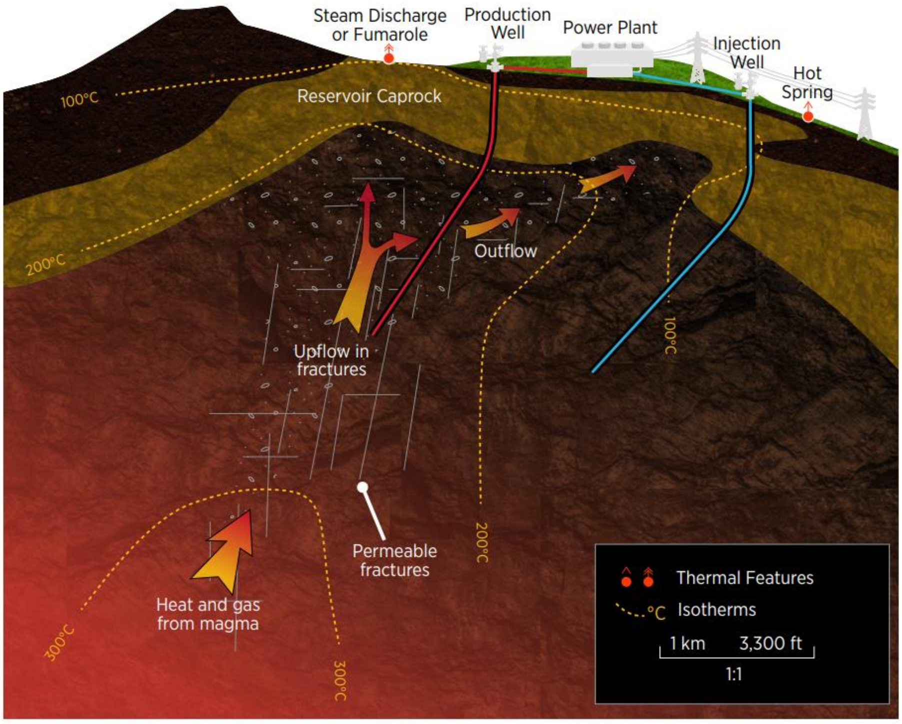

Figure 7: Hydrothermal Resource Geothermal Operation[7]

The exploitation of conventional geothermal has focused, to date, on sites where the resource is relatively easy to access, and the resource temperature is high enough for the operation to be commercially viable. Temperatures greater than 150°C are typically required for a hydrothermal resource to be used to generate electricity.

Where temperatures are below 150°C the heat resource can be used directly (direct use), in district heating for example, where water from the geothermal resource is piped through heat exchangers or directly into commercial or residential buildings. The use of conventional geothermal resources for heat and power is not new. Conventional heat resources have been used by the Mãori[8] for heating, cooling,

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7 GeoVision, US Department of Energy, May 2019

8 New Zealand Government: Ministry of Business, Innovation and Employment (no date). Geothermal Energy Generation. Available at: https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/energy-generation-and-markets/geothermal-energy-generation/, [accessed: 02/12/2021].

and therapeutic purposes since the 1870's, and power generation from conventional resources began in 1904 at the dry steam field of Larderello, Italy[9]. Modern power modules, such as those developed by Climeon in Sweden, can now generate electricity from temperatures as low as 80°C.

3.1.2 Engineered Geothermal Systems

The term engineered or enhanced geothermal systems (EGS) refers to the practice of creating a geothermal reservoir in hot rock by injecting water into wells to create fractures.

The process has generated considerable interest as EGS can be applied wherever there is hot rock at accessible depths, which is nearly everywhere on the planet. Also, EGS can be applied to conventional hydrothermal resources and geothermal plants where, for various reasons, the plant is no longer commercially viable – this is referred to as "in-field" EGS. The technique could be used to engineer connections from unproductive geothermal wells to additional geothermal reservoirs and so result in additional heat recovery.

Following "in-field", the next logical application of EGS is "near-field", where EGS operations are created near an existing conventional geothermal plant. In this application the technology takes advantage of the zones of hot rock and the permeable reservoir area is expanded through enhancement of periphery reservoir permeability.

The third application potential of EGS is "deep" EGS, which would be a standalone operation where high temperature rock is accessed by drilling.

EGS has been applied at pilot and demonstration scale at conventional hydrothermal sites to explore innovative ways to stimulate wells.

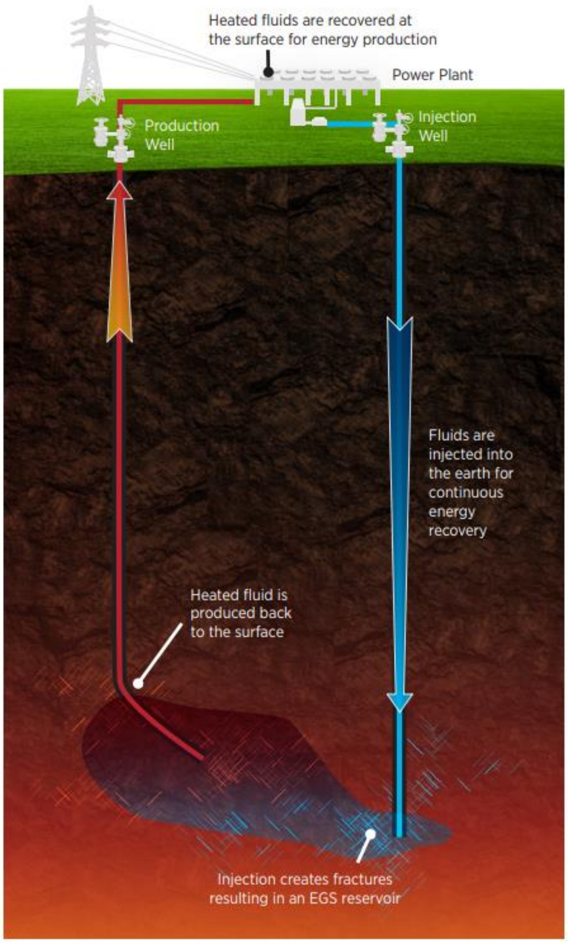

Figure 8: Typical EGS System[10]

This is an active area of research, particularly in the USA, as the technologies required for EGS are similar to those used for hydraulic stimulation in the oil and gas industry. However, new technologies are required to improve well productivity and lower development costs[7], including:

- Lower cost drilling tools and drilling methods
- Improved reservoir stimulation technologies
- New modelling tools

9 Unwin, J (2019). The Oldest Geothermal Plant in the World. Available at: https://www.powertechnology.com/features/oldest-geothermal-plant-larderello/ [accessed: 02/12/2021)

10 GeoVision, US Department of Energy, May 2019

The technology challenges and hence opportunities for the oil and gas within EGS are discussed in detail in Section 4 of this report.

3.1.3 Closed Loop Geothermal

Closed-loop geothermal (CLG) systems use sealed wells to circulate a heat transport fluid through the subsurface. This eliminates the need for geothermal fluid flow from the reservoir formation to the surface. Depending on the temperatures available, CLG can be used to produce electricity and/or for heating.

CLG has attracted considerable attention as an advanced geothermal system and it has several advantageous features. Firstly, there is no fluid exchange with the reservoir or surrounding area – the geothermal fluid is not circulated. It is, therefore, an attractive option in countries where, for cultural reasons, or countries that are water-stressed, conventional geothermal and EGS are not appropriate. Secondly, CLG can be used to retrofit existing wells, which, for a variety of reasons, have become unproductive. It is a versatile technology that can be implemented in a wide range of different well pipe configurations using a choice of working fluids (such as water and supercritical CO_2 (sCO_2)) to optimise site-specific costs and performance.

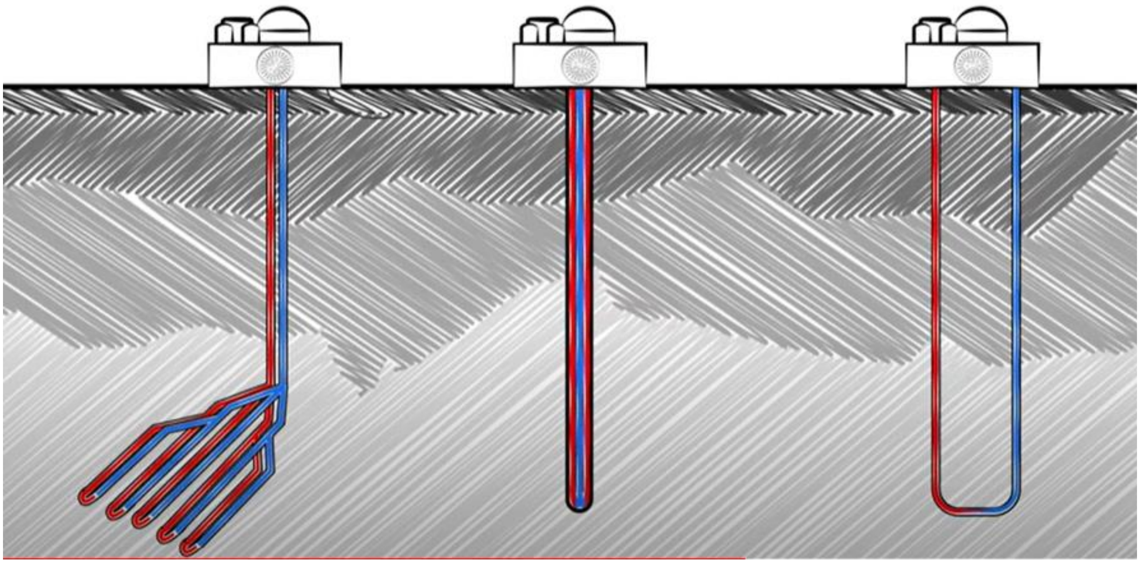

Figure 9: Different Closed-Loop Configurations[11]

CLG is not yet commercial but there are several ongoing demonstration projects, which utilise the latest innovations in directional drilling / side tracking developed in the oil and gas sector, e.g. Eavor Loop (which raised $40m from BP and Chevron earlier this year).

3.1.4 Mine Water Geothermal

Abandoned mines can be used as a geothermal energy resource, using the natural heat contained in the mine water. Heat can be extracted from the mine water by use of water-source heat pumps. As this is a low temperature resource, the heat could be used directly to either support a large heat customer

[11] Getting Geothermal Anywhere – Closed Loop Systems Technoeconomics, Pivot 2021 Conference, July 2021

(single building such as school or tower block), district heating or to feed into industrial applications, such as heating greenhouses.

Mine water resource can be accessed via four options:

- Via mine water treatment plants
- From surface gravity discharges (artesian mine water)
- Via old mine shafts
- Drilling purpose-built boreholes

Accessing mine water heat via mine water treatment plants is the most convenient and cost-effective way, assuming the Coal Authority retains most or all of the operational cost of the mine water treatment which can be a costly process. In the UK the Coal Authority has 75 of these treatment plants and they are used to treat mine water to ensure it is safe to discharge into surface waters or aquifers. Accessing mine water via old mine shafts would have been another convenient option, however many of these were filled and capped when mines were closed. Drilling boreholes, to tap into known reservoirs of mine water, is the most expensive way of accessing mine energy but also the most flexible as it allows end users to access the resource close to existing and planned sources of demand.

3.2 Geothermal Electricity Generation

In its geothermal roadmap, the International Energy Agency (IEA) projected that geothermal electricity will produce 1,400 TWh annually by 2050, from a global capacity of 200 GW.[12] This would account for around 3.5% of global electricity production at that time. The scenario assumes renewable energy would provide 75% of global electricity production in 2050.

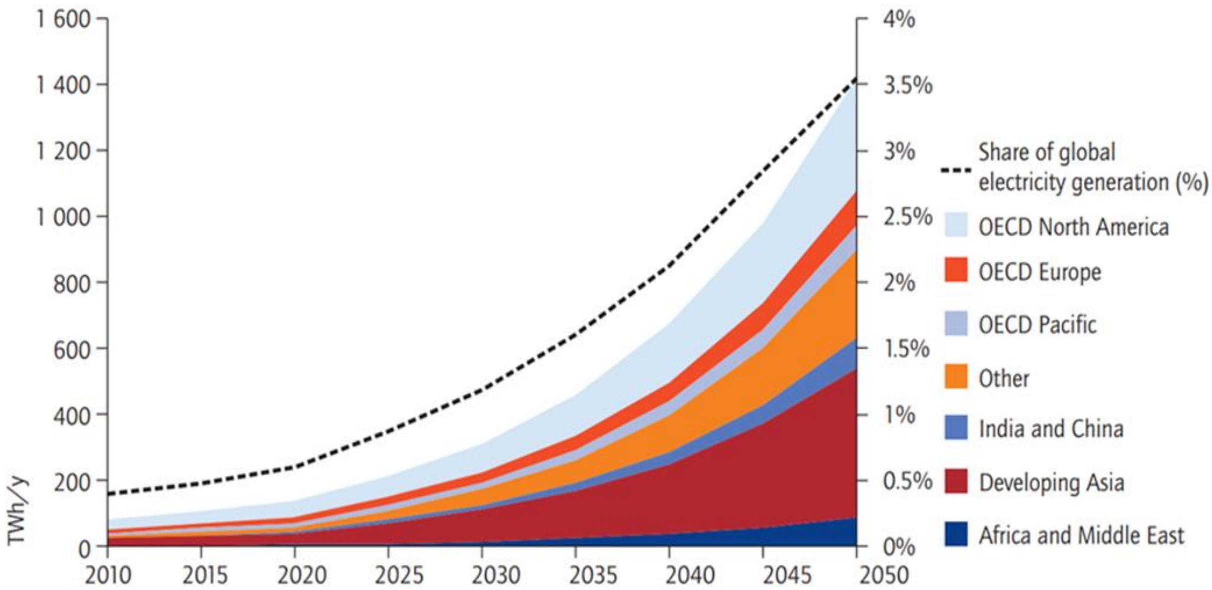

Figure 10: Predicted Market Growth by Region - Geothermal Electricity Generation

Both conventional and hot rock geothermal technologies are expected to be developed and contributing to capacity (with hot rock technologies becoming commercially viable shortly after 2030).

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12 Technical Roadmap – Geothermal Heat and Power, IEA, 2011

It is clear from the figure above that considerable growth is expected in "Developing Asia", where high temperature hydrothermal resources are abundant and are not exploited. Also, North America, and in particular western United States, is also expected to witness strong growth. European countries are expected to develop both high temperature and low temperature resource.

A projection of growth by geothermal technology is shown in the figure below.

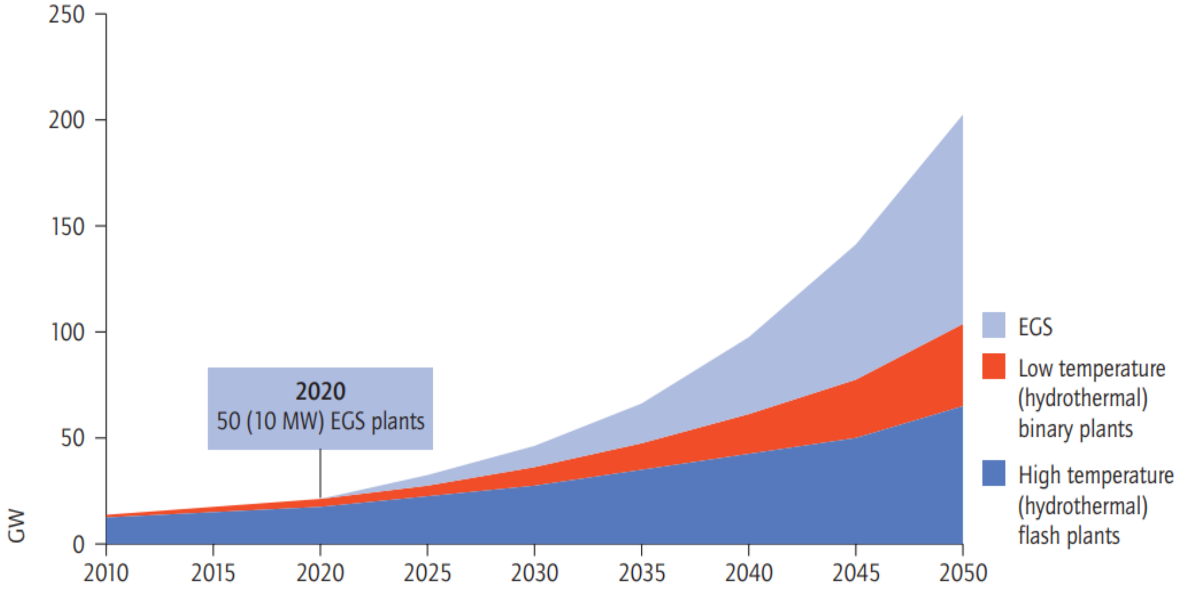


Figure 11: Predicted Market Growth by Technology

It is clear from the above figure, that the IEA sees EGS playing an increasing role in installed capacity going forward. Also, as technology improves there is the option of using lower temperature geothermal resources for electricity production – at lower temperature the technology used for geothermal power generation, almost exclusively corresponds to Rankine cycle (binary) power plants. In these plants, the geothermal fluid transfers its heat to a closed loop of a working fluid and the vapour of which drives a turbine for electricity generation.

The map below shows the distribution of geothermal electricity plants around the world.

Figure 12: Distribution of Geothermal Power Plants[13]

In its annual market report[14], the EGEC (European Geothermal Energy Council) estimated that Europe has an installed geothermal electricity capacity of 3.5 GWe in 2020, distributed over 139 power plants. As shown in the figure below, there has been considerable new installation activity in Turkey.

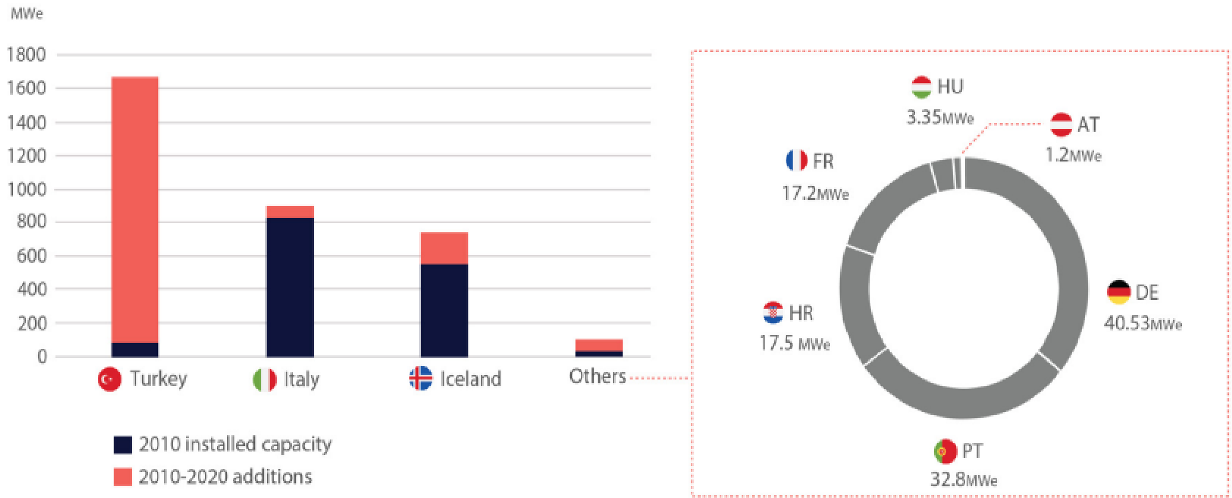


Figure 13: Recent Capacity Growth – Geothermal Energy Generation in Europe

Other leading countries in Europe include Italy, Spain and France. No country commissioned a geothermal power plant in 2020, due to the COVID pandemic.

13 www.Thinkgeoenergy.com

14 Geothermal Market Report, EGEC, June 2021

As just mentioned, Turkey is however continuing to expand, and the recent extension of the feed-in tariffs for geothermal plants will maintain the positive trend in this market.

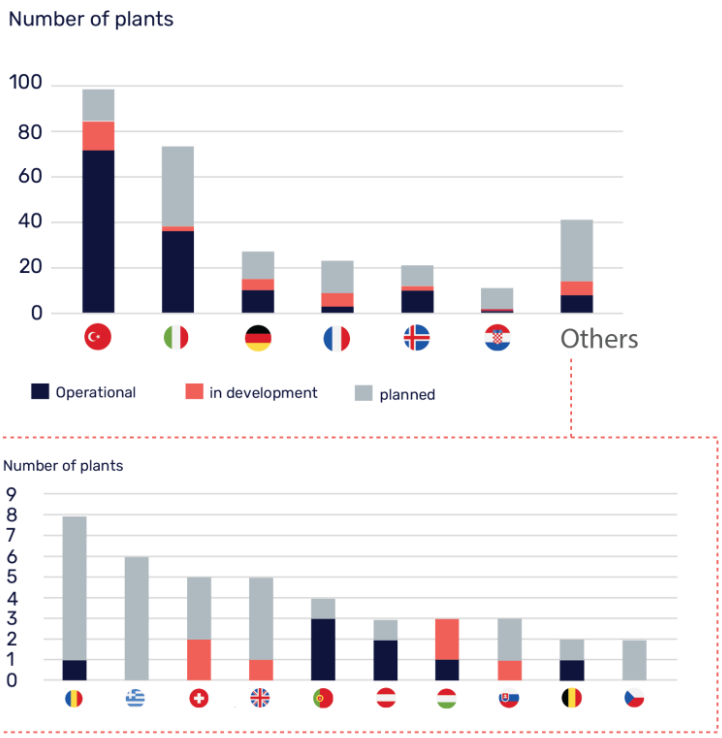


Figure 14: Number of Geothermal Power Plants in Europe

Figure 15: Distribution of Geothermal Power Plants in Europe

3.3 Geothermal Direct Heat Use

A wide range of geothermal temperatures can be used for heating in applications such as space and district heating, spa and swimming pool heating, greenhouse and aquaculture ponds heating, and for industrial processes. This is commonly referred to as direct use.

The IEA predicts that direct use could amount to 5.8 EJ/yr (about 1 600 TWh thermal energy) by 2050[12]. The scenario assumes technologies such as EGS will become commercially viable shortly after 2030 and will be in direct use applications in addition to electricity production.

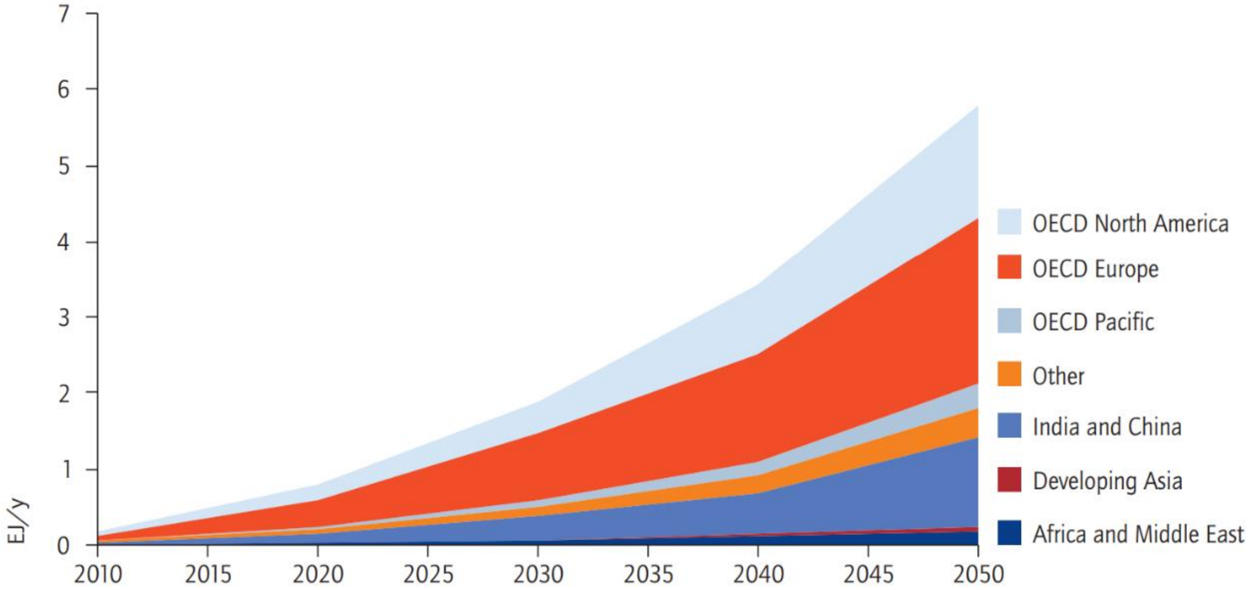


Figure 16: Expected Market Growth – Geothermal Direct Use

As shown above rapid growth is expected in Europe.

The most widely spread geothermal direct heat use application, after ground source heat pumps (49% of total geothermal heat), is for spa and swimming pool heating (about 25%), for instance in China, where it makes up 23.9 PJ out of the 46.3 PJ of geothermal heat used annually (excluding ground source heat pumps). The next-largest geothermal heat usage is for district heating (about 12%), while all other applications, combined, make up less than 15% of the total.

Geothermal 'heat only' plants can feed a district heating system, as can the residual hot water from electricity generation, which can also be used in a cascade of applications demanding successively lower temperatures. These might start with a district heating system, followed by greenhouse heating and then, perhaps, an aquaculture application – the order of application will vary to suit local temperature profiles and application needs.

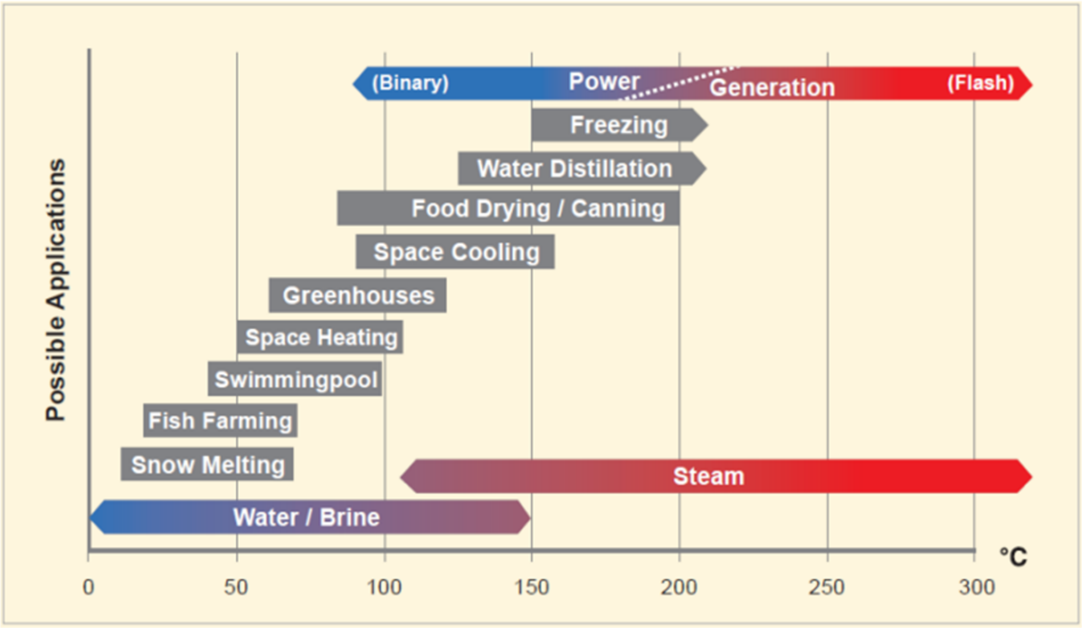


Figure 17: Direct Use Applications by Temperature Range[15]

To maximise the utilisation of heat, a cascade approach has been suggested, where heat is first used to generate electricity and then for district heating and greenhouse and aquaculture applications.

In its annual market report[14], the EGEC estimated that there were 350 geothermal district heating systems in operation in Europe in 2020 and a further 232 were at various stages of development. On average, 12 projects were commissioned per year. A segmentation, by country, of the number of geothermal district heating and cooling systems in operation and those in development is provided in the figure below:

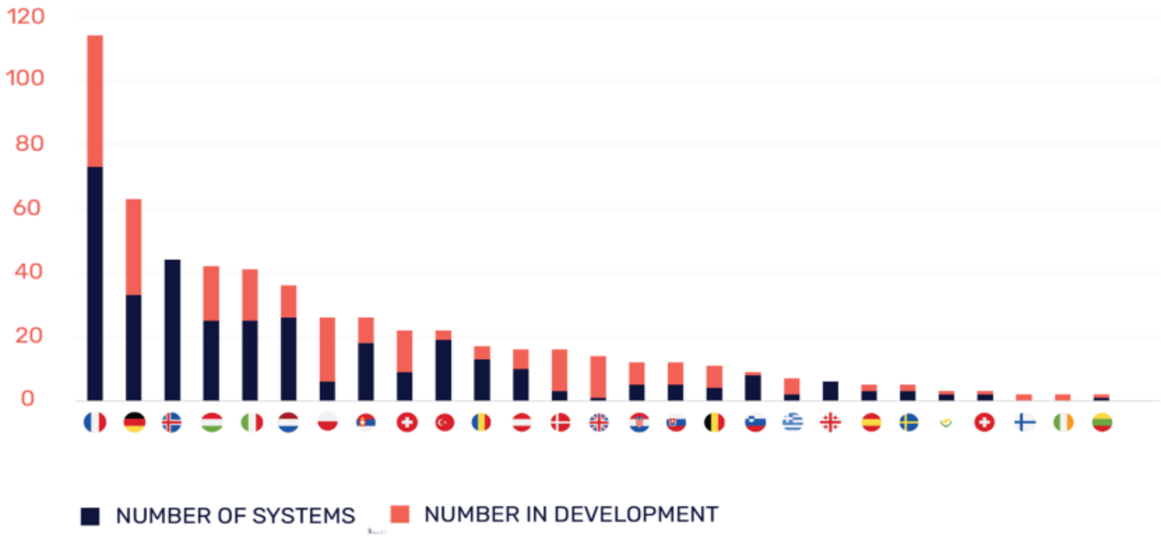


Figure 18: Development of Geothermal Direct Use Plants in Europe

15 https://www.esmap.org/sites/esmap.org/files/DocumentLibrary/1Overview%20of%20direct%20geothermal%20applications%20%C3%81rni%20R.pdf

An indication of growth over the last 10 years is show in the figure below.

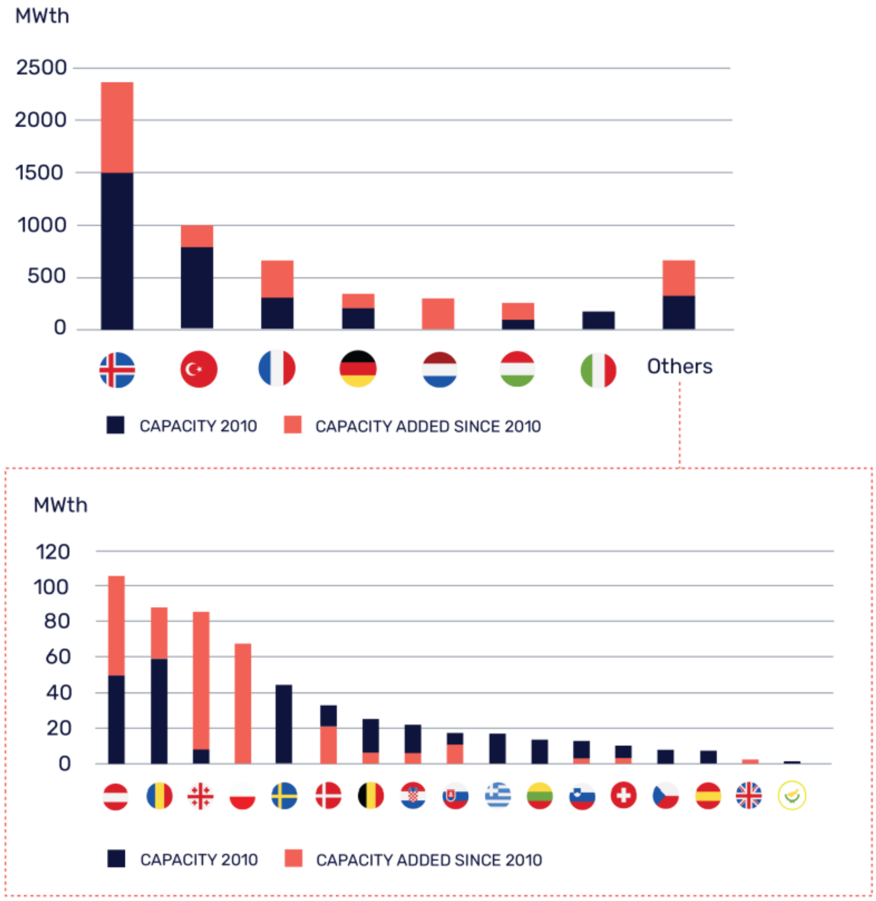


Figure 19: Recent Growth - Geothermal Direct Use Plants in Europe

3.4 Abandoned Mines – Space Heating

Although the first use of mine water as a heat resource was reported back in 1981 in the US, and it is estimated there are over 1 million abandoned mines worldwide, the opportunity to use abandoned mines as a geothermal resource has not developed. There are only a small number of installations worldwide, estimated at fewer than 30, spread across a few countries, namely North America, Spain, Italy and the UK. Projects are also now emerging in China, a country which leads the world in direct use geothermal heat networks.

The UK Coal Authority estimates that there are 23,000 abandoned deep coal mines around the UK, as shown below, and have estimated that 25% of UK housing sits above a coal mine.

Figure 20 The Mine Water Potential In the UK

Although growth has been slow, there are several examples of abandoned mines being used successfully as geothermal resources. For example, the largest mine wate- based heating system in the UK is installed by the Gateshead company, Lanchester Wines. The company is using an open loop water source heat pump system with a 2.4MWth and 1.6MWth installed capacity. The system is operated, including optimisation, maintenance and regulatory engagement, by Edinburgh based geothermal consultancy TownRock Energy.

The Coal Authority estimate that there are 42 projects in the UK pipeline. Examples include:

- The council-owned Gateshead Energy Company is in the process of installing a 6MW waster source heat pump to feed into an existing district heating network
- Durham County Council, planning to use a mine water treatment scheme to extract heat as part of a new Garden Village at Seaham. "*This development has the potential to make Seaham Garden Village the first large scale mine energy district heating scheme in the UK*."[16] The scheme will consist of 750 affordable homes, 750 private homes, a school, shops, and medical and innovation centres.

The main barriers preventing the development of mine water as a geothermal resource include:

16 The Case for Mine Energy – unlocking deployment at scale in the UK, White Paper, North-East LEP

- Uncertainty over support schemes - projects that have explored mine water have been very dependent on public support schemes, such as, Network Investment Programme (HNI), the European Regional Development Fund (ERDF), or the renewable heat incentive (RHI). There is a great deal of uncertainty over what support schemes will be available in the future. Clearly, mine water geothermal needs to be sustainable without reliance on such schemes.
- Coal Authority plans for a potential access charge - the Coal Authority is expected to charge for access to heat from mine water treatment schemes, but not from borehole-based schemes. There is uncertainty over what this charge is likely to be, but considering the marginal economics, any charge may render mine water geothermal commercially unviable.
- Cost of borehole-based schemes - as discussed earlier, the most favourable access route to mine water is via the treatment plants run by the Coal Authority. However, these plants may not be conveniently located and/or far from the user base. Access via boreholes, in terms of proximity to users, is the best option, but the costliest. The high cost of boreholes is a major barrier
- Decline of projected heat over time - the risk of heat depletion is another major barrier. There is concern that, although at first, the heat resource would appear to be sufficient to support the planned scheme, over time this resource could be depleted and result in unviable operation. Sophisticated systems, such as in Heerlen, provide both heating and cooling to customers, which when approximately balanced greatly mitigates this risk

A summary of most important challenges in mine water geothermal is presented in the figure below:

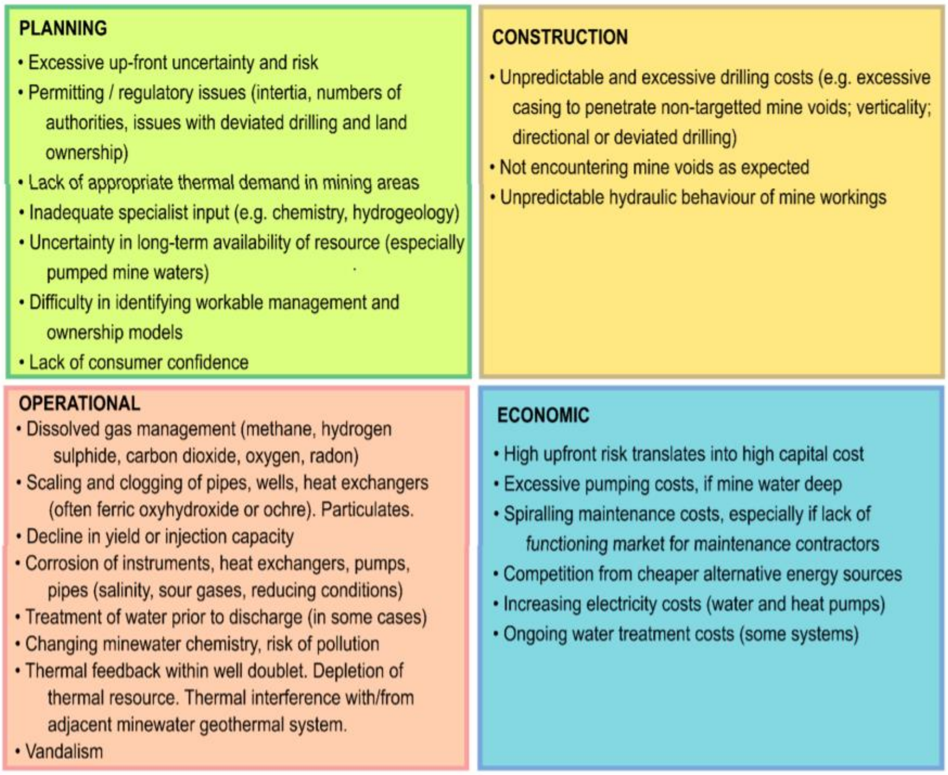


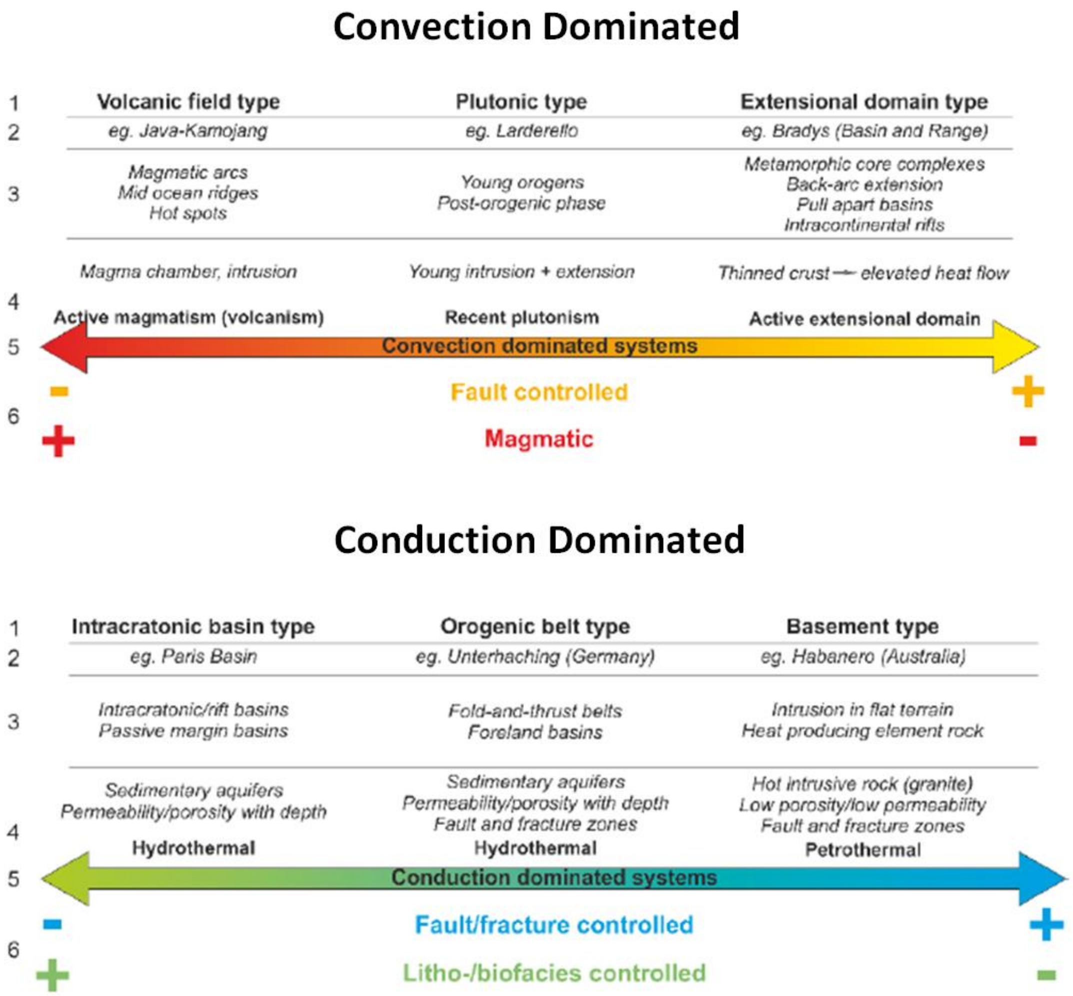
Figure 21: Mine Water Geothermal Challenges[17]

[17] A Review of the Performance of Minewater Heating and Cooling Systems. Energies 2021, 14, 6215.

The need for solutions to address the technological barriers identified above are discuss in Section 4 of this report.

3.5 Defining Geographic Markets

The opportunity to develop different types of geothermal energy generation is based, predominantly, on the geological and environmental characteristics of different regions. A method of categorising geothermal energy generation, based on geological characteristics, referred to as "geothermal plays", has been developed[18]. It identified six different plays, based on geological and environmental characteristics, which can be summarised as follows:



Key: 1 – Play type | 4 – Geologic habitat of potential geothermal reservoirs
2 – Type locality | 5 – Heat transfer type
3 – Plate tectonic setting | 6 – Geologic controls

Figure 22: A Catalogue Scheme Summary of Geothermal Plays (after Moeck, 2014)

18 Catalog of geothermal play types based on geologic controls, Moeck, I.S., Renewable and Sustainable Energy Reviews, Volume 37, September 2014

However, this analysis also highlights that most locations show characteristics of more than one type.

It further indicates that each of these plays are present in a number of different locations, due to their similar geological conditions. Each of these plays is classified in Appendix B in terms of tectonic setting, regional examples and countries / territories together with a brief description and an overview of the main technical challenges. One example, for extensional domain type, is included below for reference.

Dominant Geothermal Type	Tectonic Setting	Examples	Countries / Territories	Brief Description	Main Technical Challenges
Extensional Domain	Intracontinental Rift (failed)	Rhine Valley	Germany	Fault controlled - plates pull apart (divergent plate boundary), crustal thinning, elevated heat flow at the surface, convection dominated heat transfer, rift border faults inactive, intra-rift faults act as permeability zones for fluid migration (groundwater, magma, brines)	Heat flow is often lower than that observed at active rifting centres. Permeability can be varied and depends on the age of the structures, time passed for fluid flow, mineral precipitation and fault sealing under natural state conditions. Likely to require manual stimulation/EGS. Porosity can also be an issue where sediments have become buired and, as a result, compacted. Drilling challenges where granite has a role. Infrastructure resilience (e.g. locations close to seismically active areas)
			France		
		Oslo Graben	Norway		
		Central Lowlands	Scotland		
		Worcester Basin	England		
		Central Graben, Viking Graben	North Sea		
		Vättern	Sweden		
		Lucapa Graben	Angola		
		Lambert Graben	Antarctica		
		Narmada River Valley	India		
		Godavari River Valley	India		
		Baikal Rift Zone, Moma Graben	Russia		
		Büyük Menderes Graben	Turkey		
		Unzen	Japan		
		Guanabara Graben	Brazil		
		Firth of Thames (inc. Hauraki Graben)	New Zealand		
		Gulf St. Vincent	Australia		
		Tamar Valley	Australia		
		Eastern North America Rift Basins	Canada		
			USA		
		Midcontinent Rift Systsem	Canada		
			USA		
		Salton Trough	Mexico		
			USA		
		Ottawa-Bonnechere Graben	Canada		
		Saguenay Graben	Canada		
		Numerous locations	USA		
		Guatemala City Valley	Guatemala		

Figure 23: Classification - Extensional Domain Type

This shows that the same types of geological conditions are found in a range of locations, albeit with location specific characteristics so the same type of geothermal energy project could be developed in these locations.

In the following section we have identified the leading geographic markets for geothermal energy generation, but the above analysis has been included to highlight that technologies developed for one specific geographic market are very likely to be relevant in other locations due to the similar geological conditions and, as a result, technical challenges.

3.6 Key Geographic Markets

A breakdown of the geothermal installed power generation capacity by country is provided in the figures overleaf. Its shows that:

- The US is the leading country in geothermal electricity production and is continuing to invest in new geothermal electricity plants. Also the US, via the US Department of Energy, is continuing to support development of EGS and advanced geothermal concepts
- Indonesia has accelerated its exploration of geothermal options. It is now 2nd only to the US regarding geothermal electricity production and has huge potential, with intentions to quadruple installed power generation capacity by 2030.
- Turkey witnessed a rapid expansion in geothermal electricity production over the last decade and it is expected that it will continue to grow the industry, primarily due to supportive regulation, policy and subsidies.

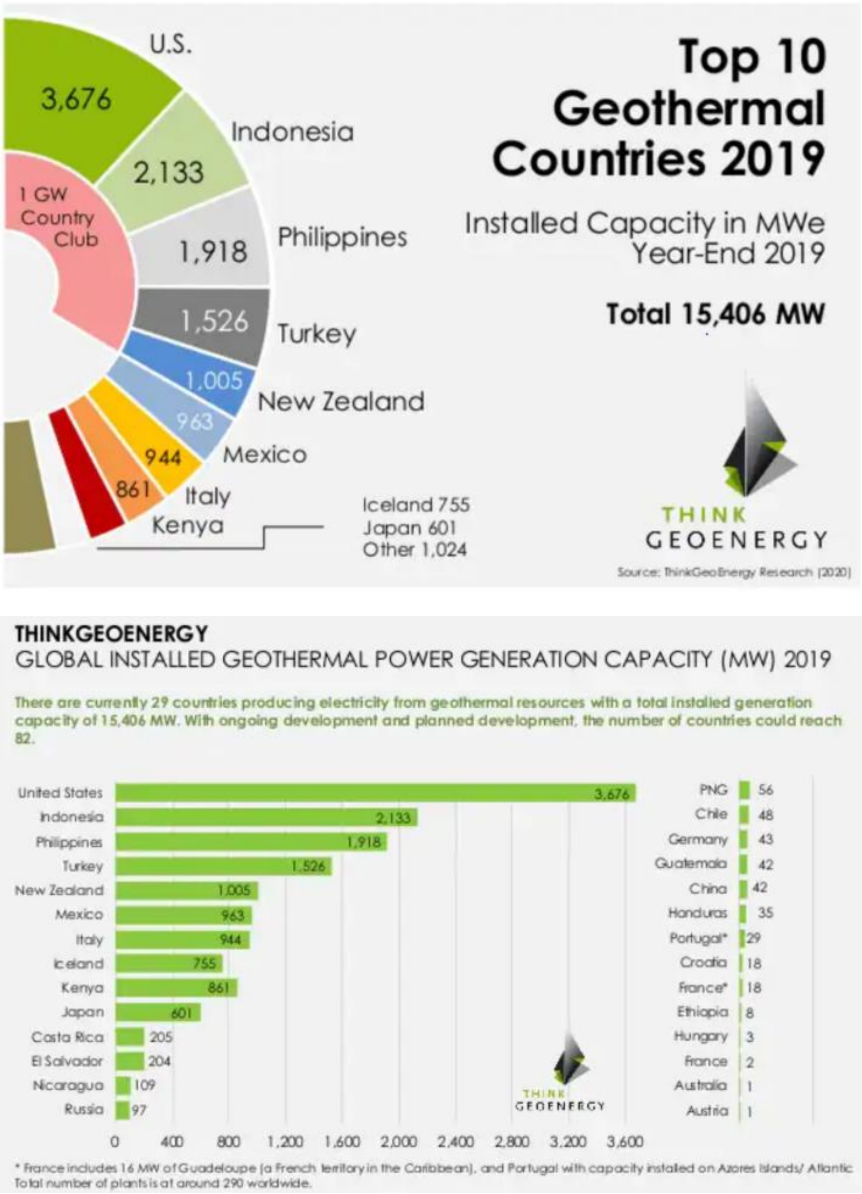


Figure 24: Global Installed Geothermal Power Generation[19]

19 https://www.thinkgeoenergy.com/

A breakdown of planned project by country is shown in the figure below. It is clear from this data that Indonesia is set to become the leading geothermal market.

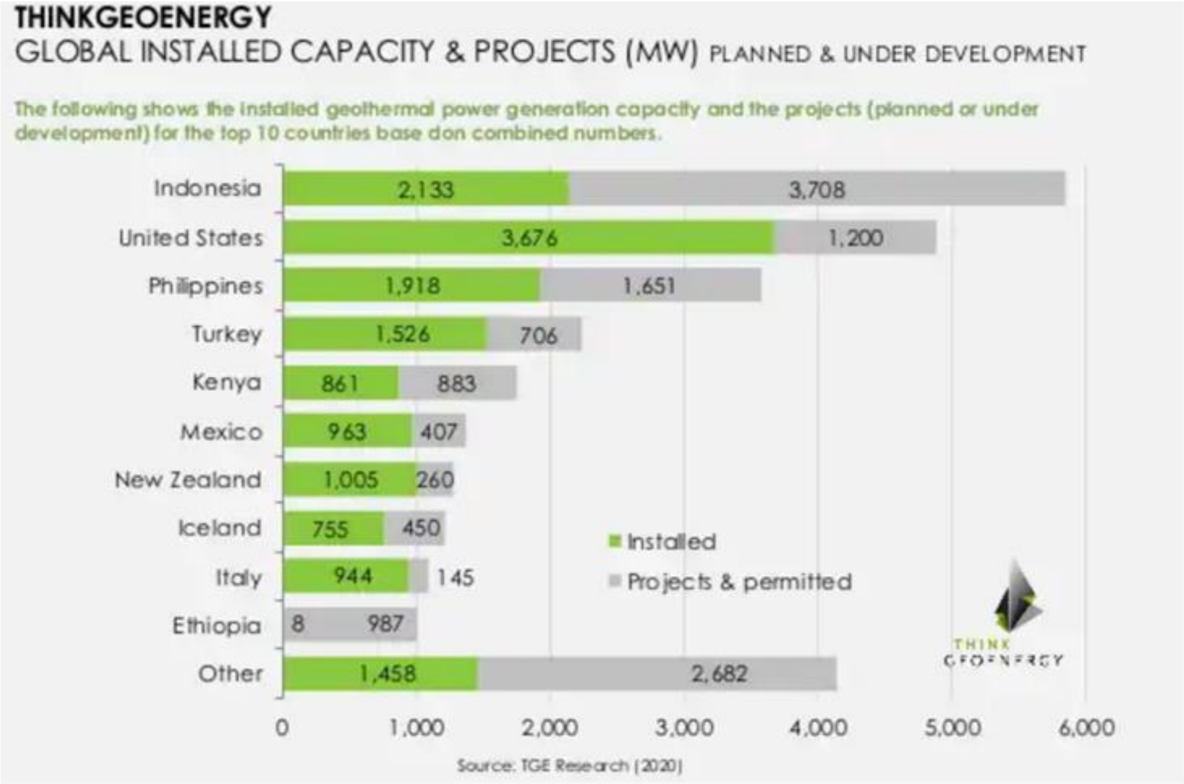


Figure 25: Planned Geothermal Projects[13]

In the sections that follow we provide more detail on the three top geothermal markets, US, Indonesia and Turkey. As a contrast we also profile German as a good example of the potential in Europe. Germany has good geothermal resources and the Government is very committed to increasing renewable energy.

3.6.1 United States

The US leads the world in geothermal electricity generation. By the end of 2019, the US had an installed capacity of 3,673 MW, across 93 geothermal power plants, mainly in western United States, where there are natural geological features that result in accessible hydrothermal fields. California and Nevada contribute more than 90% of the current U.S. geothermal power generation.[20]

20 2021 U.S. Geothermal Power Production and District Heating Market Report, NREL

Figure 26: Geothermal Electricity Plants in Western United States[21]

From 2015 through to the end of 2019, the US brought seven new geothermal power plants online in Nevada, California, and New Mexico, adding 186 MW of capacity. In the same time period, 11 plants were retired or classified as non-operational, subtracting 103 MW of nameplate capacity.

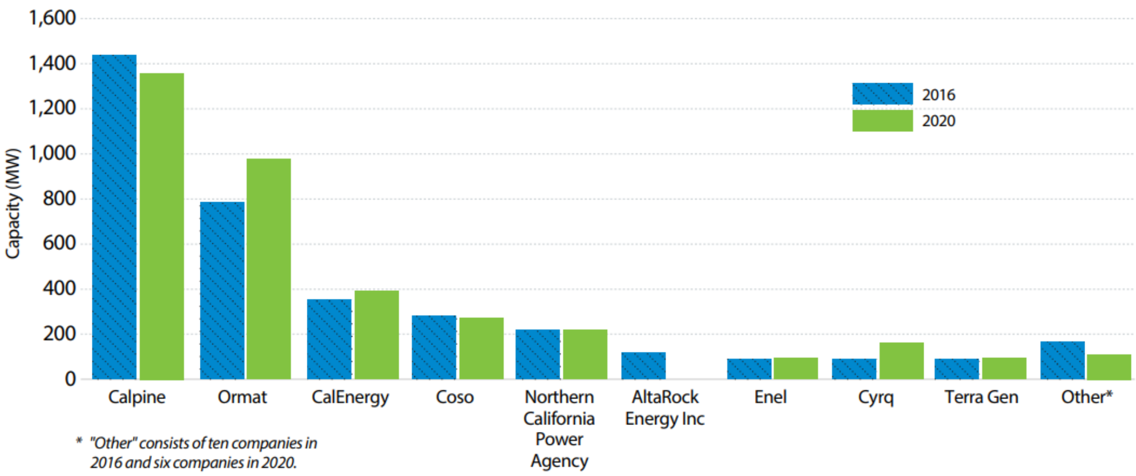


Figure 27: US Geothermal Power Plant Capacity by Operator

As shown in the figure above, the US geothermal power industry is dominated by two operators, Calpine and Ormat. In terms of project pipeline, geothermal companies operating in the United States have a

21 https://www.thinkgeoenergy.com/map/

combined 58 active development projects and prospects across nine states, with the majority located in Nevada. Lithium recovery from geothermal brines is an important factor in securing private investment of these projects, as has been the case in Cornwall, UK.

Currently, there are 23 geothermal district heating (GDH) systems in the United States, with a capacity totalling more than 75 MW of thermal energy (MWth). The majority (15 of 23) of the existing U.S. GDH systems were installed in the 1970s and 1980s, and all but one of these are still operating.

Regarding government support, the US government, through the Department of Energy (DOE), continues to support research and development into geothermal technologies, particularly emerging technologies such as EGS. The DOE recently announced $12 million in funding for seven research projects to advance the commercialisation of enhanced geothermal systems (EGS)[22]:

- Cornell University: $2.3 million
- Lawrence Berkeley National Laboratory: $1.7 million
- Missouri University of Science and Technology: $2.3 million
- Montana State University: $1.5 million
- Oklahoma State University: $1.0 million
- Pennsylvania State University, University Park: $1.0 million
- University of New Mexico: $2.0 million

3.6.2 Indonesia

Indonesia is one of the most geologically active countries in the world, with an estimated 40% of the world's geothermal resource. However, this potential remains largely untapped. This was because, under the country's legal framework, geothermal activities were classed as mining activity and, so, were prohibited in the country's many protected forests and conservation areas. Some 80% of the country's geothermal resource is in these areas[23]. Acknowledging that geothermal activities, compared to mining, have minimal environmental impact, the governing law was changed in 2014, and the Geothermal Law was passed that separated geothermal from mining. In addition, the Indonesian government made funding available, through the Geothermal Fund Facility (GFF), to help mitigate the high upfront costs of geothermal exploration.

As a result of these measures, Indonesia overtook the Philippines in 2018 to become the second largest geothermal electricity producing country globally, behind only the United States. The Indonesian government is aiming to expand its installed capacity, increasing from 2.1GW currently to reach 8 GW of geothermal capacity by 2030.[24] This forms part of the government's aim to source 23% of its energy from renewables by 2025.

22 U.S. DOE announces $12m boost to geothermal energy research, Think GeoEnergy, 22 Sep 2021

23 Indonesia Investment Authority, https://www.ina.go.id/

24 Indonesia sets eyes on becoming world's geothermal superpower, Eco-Business.com, July 2021

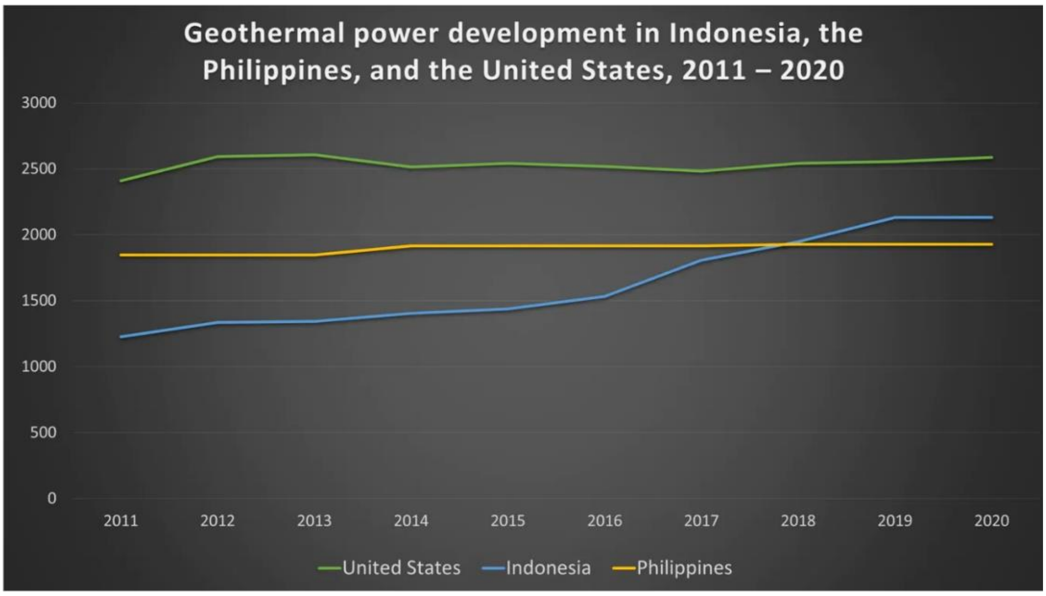


Figure 28: Comparative Growth of Geothermal Power Development in Indonesia, The Philippines and United States[24]

To date, a total of 16 geothermal power plants have been built in Indonesia. The country has 19 existing Geothermal Working Areas (WKPs), 45 new WKPs and 14 Assignment Areas for Preliminary Survey and Exploration (WPSPE)[25].

The Geothermal Director of the Directorate General of EBKTE at the Ministry of Energy and Mineral Resources, Ida Nuryatin Finahari, has stated that the government will provide incentives to reduce developer risks. To achieve the geothermal development target in 2030, at least 41 WKPs are planned.

The Indonesian state-owned electricity company, PT PLN, recently announced plans for 21 renewable energy projects in 2022, including drilling contract tenders for seven geothermal projects. These geothermal projects include opportunities for drilling contracts and the supply of well related materials and equipment.

Figure 29: Investment Announcement in Indonesia[26]

3.6.3 Turkey

In the last decade Turkey has witnessed huge growth in the utilisation of geothermal resources for electricity production and direct heat use. The country is rich in natural geothermal resource, with around 450 geothermal fields discovered to date, and the Turkish government has put in place a supporting legal framework to facilitate geothermal development.

Regarding geothermal electricity generation, installed capacity had reached 1,282.5 MWe at the end of 2018. The country's total geothermal electricity production potential, for hydrothermal resource within

25 Indonesia remains focused on becoming world top ranking geothermal country, Think Geoenergy, August 2020
26 PTN PLN to issue tenders on 7 geothermal projects in 2022, Think Geoenergy, 25 November 2021

4km depth, has been estimated as 4500 MWe. The growth of geothermal electricity is shown in the figure below[27].

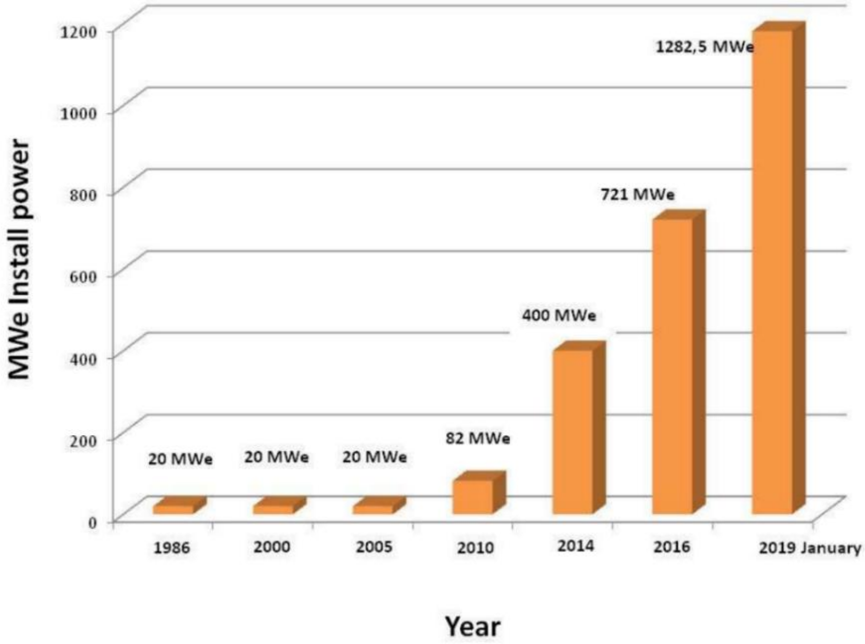


Figure 30: Geothermal Electricity Capacity in Turkey

As of February 2019, there were 55 operating geothermal power plants at 26 geothermal fields in Turkey. The country is drilling to reach fields at depths to 4.5km and exploiting resources at temperatures above 240°C. The country has set a target of 2,600 MWe for geothermal electricity by 2025.

Geothermal direct use was estimated to have reached 3,487 MWt in 2019. This comprises:

- district heating (1033 MWt),
- greenhouse heating (820 MWt),
- commercial heating (420 MWt),
- balneological use (1205 MWt),
- agricultural drying (1,5 MWt),
- geothermal cooling (0,1 MWe),
- heat pump (109 MWt) and ground source heat pump applications (7,6 MWt).

There are 17 city district heating operations in place.

As highlighted earlier, in addition to the abundant natural resource, Turkish government policies have been the main driver of growth. The Geothermal Law of 2007, set out the rules and principles for effective exploration, development, production and protection of geothermal and natural mineral water resources. In 2010, a feed-in tariff of 105 USD/MWh, guaranteed for a 10-year period from commissioning, was introduced. In addition, up to 27 USD/MWh, guaranteed for a 5-year period from commissioning, was introduced to support use of locally produced equipment[28].

27 Geothermal Energy Use, Country Update for Turkey, European Geothermal Congress 2019
28 Towards More Geothermal Power in Turkey, World Geothermal Congress, October 2021

Earlier this year the Turkish energy regulator announced new 10-year feed-in tariffs for renewable power projects commissioned between 1 July 2021 and 31 December 2025. These feed-in tariffs will be subject to quarterly increases, based on a range of economic price indices. Geothermal projects will receive TRY 54c/kWh (€6.22c/kWh)[29].

> *Turkish geothermal operator and developer, Greeneco Enerji, has announced plans for a 49 MW expansion of the Greeneco geothermal plant complex in the Sarayköy, Denizli area in Turkey. The planned investment value is TRY 978 million (approx. $80m as of Nov 25, 2021). With the seventh power plant to be established by the company, it is expected to increase its total installed power to 155 MW.*

Figure 31: Investment Announcement in Turkey[30]

3.6.4 Germany

Germany is increasingly exploring use of its geothermal resource to generate heat for direct use. There were 38 geothermal power and heating plants in operation in Germany in 2020. Nine of these plants generate electricity, with a total installed capacity of around 47MW and the remaining generate heat for direct use, with an installed capacity of 350 MWth[31].

Region	Location	Mwel	MWth	Power plant
Upper Rhine Graben	Landau	0,8	5	ORC
	Bruchsal	0,44	0	Kalina
	Insheim	4,8	0	ORC
South Molasse Basin	Dürrnhaar	6,0	0	ORC
	Sauerlach	5,0	4,0	ORC
	Kirchstockach	6,0	0	ORC
	Oberhaching-Laufzorn	4,3	40	ORC
	Oberhaching-Taufkirchen	4,3	35	ORC
	Traunreut	5,5	12	Kalina

Figure 32: Electricity Producing Geothermal Plants in German (Jan 2020)[31]

Germany has relatively good geothermal resources. The three most interesting areas are found in the North German basin, the Upper Rhine Plain and the Molasse basin, offering temperatures of 60°C to 100°C at a depth of a few kilometres.

Germany has set itself the goal of achieving greenhouse gas neutrality in 2050. An important milestone is the implementation of the Climate Action Programme 2030, according to which renewable energies are to cover 65% of German electricity consumption in 2030.

29 https://www.enerdata.net/publications/daily-energy-news/turkey-announces-new-renewable-fit-under-yekdem-scheme.html

30 New 49 MW expansion planned for Greeneco geothermal plant, Turkey, Think GeoEnergy, 25 November 2021

31 2020 Germany Country Report, IEA Geothermal, May 2021

The German government consistently supports the development of renewable energy and has established various support initiatives, including investment subsidies, R&D funding and favourable feed in tariffs. The federal government is creating incentives to support geothermal projects under the Renewable Energy Sources Act (EEG). The EEG was amended again in early 2021, where is geothermal will continue to be supported, through favourable tariffs.

As part of the GeoFern project of the German Geo Research Centre (GFZ) Potsdam, an exploratory borehole is soon to be sunk to explore the option of integrating geothermal heat into the existing Berlin city district heating system.

Figure 33: New Project Announcement in Germany[32]

3.6.5 Tender Opportunities

As examples of the types of opportunities Scottish oil and gas companies could pursue, we listed current tenders for two of the four countries briefly profiled above.

Country	Date	Summary	Organisation	Deadline
Germany	26-Nov-21	Provision And Operation Of A Deep Drilling Rig For Drilling Deep Boreholes For The Extraction Of Geothermal Energy	ENERGIE UND WASSER POTSDAM GMBH	05-Jan-22
	19-Nov-21	Geothermal Energy Wilhelmsburg, Directional Drilling	HAMBURG ENERGIE GEOTHERMIE GMB	13-Dec-21
	13-Nov-21	Provision Of Geothermal Energy	BEZIRKSAMT TEMPELHOF-SCHÖNEBERG VON BERLIN	07-Jan-22
Turkey	02-Dec-21	The Closure Of The Geothermal Drilling Well	OTERMAL SONDAJ KUYUSUNUN KAPATILMASI ISI YAPTIRILACAKTIR	10-Dec-22
	30-Nov-21	The Work Of The Thermal Water Obtained From Geothermal Wells From Geothermal Wells On The Cubic Meter (m^3) Cost To Be Tendered	ANKARA GÜDÜL~DE JEOTERMAL KUYULARDAN ELDE EDILEN TERMAL SUYUN METREKÜP (M^3) BEDELI ÜZERINDEN KIRALANMASI ISI IHALE EDILECEK	10-Dec-21
	25-Nov-21	Geothermal Heating System And Electrical Distribution Network Construction Tender	JEOTERMAL ISITMA SISTEMI VE ELEKTRIK DAGITIM SEBEKESI YAPIM ISI IHALESI	09-Dec-21

Figure 34: Examples of Current Biothermal Tender Opportunities

More details on these tenders can be obtained from https://www.tendersinfo.com/

32 German capital Berlin exploring option of geothermal district heating, Think GeoEnergy, 22 November 2021

4 Opportunity Identification and Analysis

As part of the market assessment, we have reviewed various sources of information, including market reports, industry commentaries and expert stakeholder opinions (including sourcing evidence and opinions from the Pivot 2021 Geothermal Conference[33]) to identify geothermal developments and technical challenges that are expected to provide opportunities for oil and gas industry suppliers. These developments and challenges are discussed below by type of geothermal operation.

4.1 Conventional Geothermal

We have identified the following oil and gas relevant technical challenges in conventional geothermal operations:

- Well structure failure
- Corrosion and scaling
- High flow rates
- Failure of pumps
- Integrated design

Well Structure Failure

Failure of geothermal wells is an ongoing issue for the industry. Casing failure can have a large impact on the productivity of the well and the ongoing maintenance costs. The problem of well structure failure is most apparent in mature conventional geothermal wells, where the wells were designed according to oil and gas standards and not enough consideration was paid to the extreme geothermal environment[34]. Although geothermal and oil and gas have similar well construction, high geothermal fluid temperature can have a significant impact on casing strength. As the well heats up, radial and axial stresses build up on the casing that is cemented in place. The temperate and, therefore, the stress will increase with well depth. Also, there are dynamic conditions to contend with, with production and injection, which can lead to casing fatigue.

There is, therefore, a good opportunity for oil and gas suppliers to enter this space with innovative solutions that can address these failure issues and extend the life of conventional geothermal wells. Opportunities could include new cement formulations, the inclusion of new materials in the casing to absorb the strains generated by the temperature change, and the development of flexible couplings that allow axial movement of the casing segments. These areas have been explored in two EU funded projects GeoWell and DEEPEGS[35]

Scaling and Corrosion

Geothermal fluids contain various quantities of soluble species and dissolved gases which, under operational conditions and temperature changes, can lead to scaling and corrosion of materials. As discussed earlier, geothermal operations are very site specific, with the composition and chemistry of geothermal fluids changing from site to site. A solution at one site may not be applicable at another.

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33 https://www.geothermal-energy.org/join-the-pivot2021-geothermal-reimagined-19-23-july-2021-online/

34 Casing failure identification of long-abandoned geothermal wells in Field Dieng, Indonesia, Geothermal Energy, 7, article number 31, 2019

35 https://deepegs.eu/

The control and prevention of corrosion and scaling is, therefore, a complex problem. There is significant knowledge of this problem in the oil and gas industry that could be transferred to geothermal operations. However, it should be remembered that geothermal operations can involve high temperatures, 200°C or more, and some scaling inhibitors and pH modifiers that work well in the oil and gas industry may not be applicable in geothermal.

High Flow Rates

For geothermal operations to be commercially viable, high rates of geothermal fluid flow is necessary. Geothermal wells are generally larger in diameter than wells drilled in all other industries. This requires non-standard drilling practices and specialist tools.

The oil and gas industry's experience of developing drilling techniques for a range of different requirements/conditions is considered very relevant here.

Pump Failure

In a geothermal project, pumping is often necessary to lift the hot brine to the surface, to increase the fluid pressure or simply to move the fluid from one place to another on the surface. Electrical Submersible Pumps (ESP) is one of the artificial lift technologies that can lift geothermal hot brine. However, harsh downhole conditions and high flow rates impose heavy strain on the components, leading to frequent failures of the pump system.

ESP technology was predominantly adopted from the oil industry, so the systems were not originally designed to withstand the harsh downhole conditions and high-volume flow rates experienced in geothermal power applications. Current ESPs have a typical operational life of only two to three years, and as temperature increases, life expectancy is further reduced[36].

There is a need, therefore, for improved pump design with higher power and temperature rating

Integrated Design

Geothermal projects often have limited budgets during exploration and first production. With investment constraints, the plants may, therefore, be designed to minimise capital expenditure and establish production as soon as possible so that revenue can begin to be generated and the commercial viability of the project can be proven to investors. However, this can often result in problems a few years down the line, when structures and systems start to fail, which leads to higher operational costs which can threaten the viability of the project.

There is now growing interest in rethinking the low CAPEX model and paying greater attention to OPEX and the long-term viability of the project. As is the case with other power plants, geothermal projects should be operational for 30 years or more. This will require a much greater investment upfront on more robust structures and systems to prevent failures and lower maintenance costs.

There is an opportunity to apply oil and gas knowhow on plant design, including both subsurface and surface operations, to ensure an optimum configuration is achieved and long-term operation can be realised.

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36 Electronic Submersible Pump (ESP) Technology and Limitations with Respect to Geothermal Systems, NREL, 2014

4.2 Deep Geothermal

For geothermal to progress from the 'low hanging fruit', where heat is close to the surface because of a geological feature, and to consider 'geothermal anywhere', deep drilling at 7km to 10km into hard rock is an ambitious but lucrative opportunity. In addition to the challenges associated with high temperatures (at over 250°C), there are numerous additional challenges such as ensuring effective and reliable instrumentation and sensing. We have identified the following oil and gas relevant technical challenges in very deep geothermal operations:

- New drilling techniques
- New tools
- Improved modelling and simulation
- Minimise maintenance
- Improved sensors

New Drilling Techniques

New drilling technologies are under development as innovators in this field try to develop solutions that will enable deeper drilling into very hard rock formations. Some companies are even suggesting it could be possible to drill down to 20km and reach temperatures of 500°C. As an example, these new techniques include:

- Companies like Quaise Energy are developing techniques that use millimetre waves at high frequencies to melt and vaporise rock – see overleaf
- Other companies such as HyperSciences are developing technology to fire small projectiles at hypersonic speeds to blast rock
- A company called GA Drilling is developing technology that uses plasma energy to destroy the hard rock.
- Imperial College London is part of an EU Horizon 202 funded project[37] consortium looking at the development of drilling systems that combines a high-pressure water jet and a high-power advanced hammer action to drill through hard rock and depth.

[37] https://www.orchyd.eu/

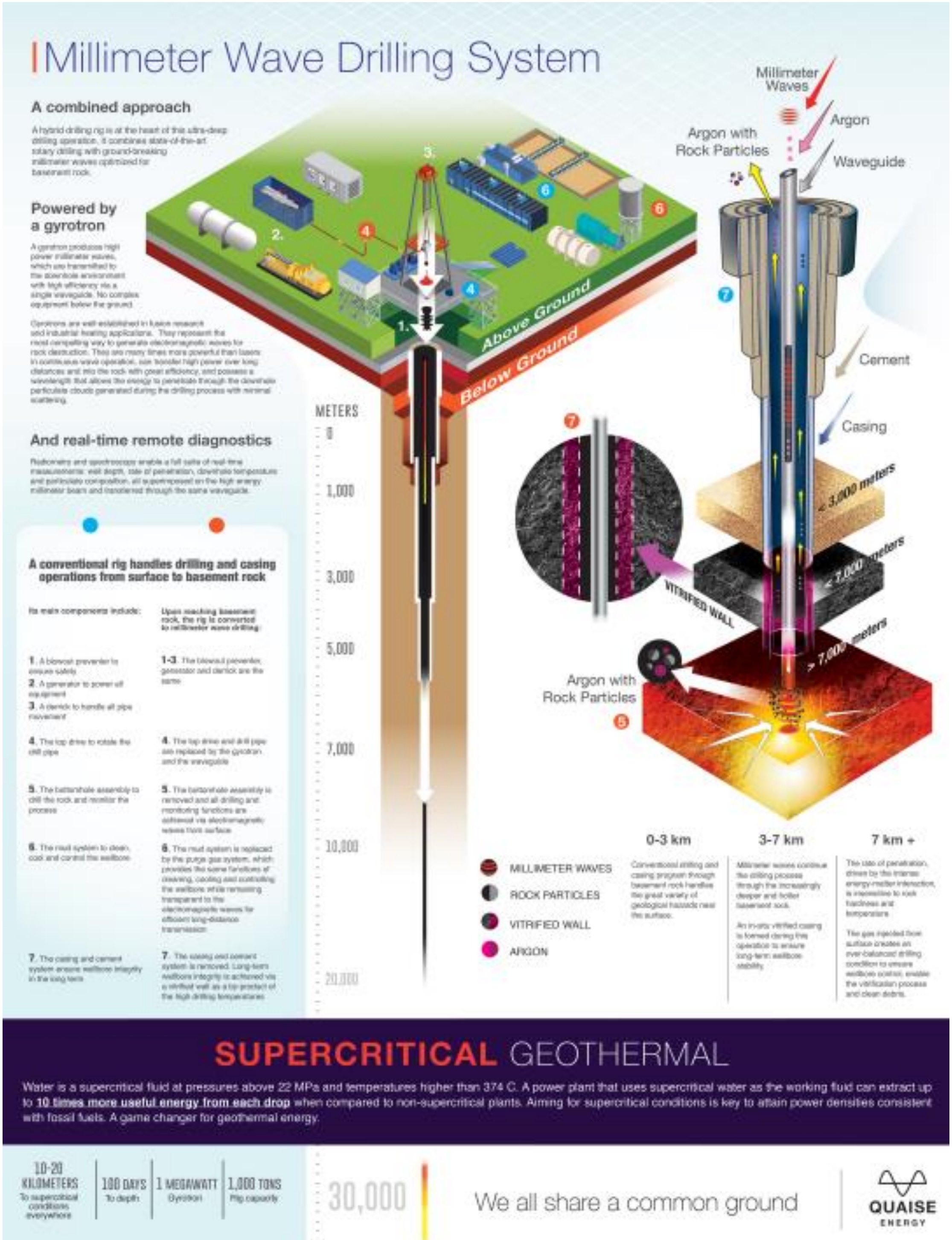

Figure 35: Schematic – Millimetre Wave Drilling System[38]

There are a broad range of drilling options under exploration and many of the companies involved are now at the stage of conducting initial field trials. There are, however, many technical challenges to overcome, such as how to effectively deliver the power these techniques require from topside down

38 https://www.quaise.energy/

many kilometres. Oil and gas companies that have aligned capabilities and expertise could have an offering to support these developments.

New Drill Tools

When drilling in hard formations, higher weight-on-bit requirements generate frictional energy, which can lead to cutting element damage and inhibit drill bit performance. The industry has relied on tungsten carbide-based bits but is now seeking alternative solutions. For example, polycrystalline diamond compact cutters on the cutting faces of bits allow more aggressive drilling than bits traditionally used for geothermal drilling.

In addition to drill bits, there is an opportunity for new drill drive mechanisms - systems that can more efficiently and effectively deliver power to the cutting bit. For example, percussive drilling is used to enhance rock penetration rates. However, conventional percussive drilling is driven by compressed air which will not work at high pressures, so alternative methods, such as fluid driven systems are required.

Modelling and simulations

The development of deep geothermal operations will require improved modelling and simulation tools. Often, downhole sensor data is limited and, sometimes, unreliable. A detailed and dynamic model system could serve as the basis for deeper understanding and analysis of the overall behaviour of geothermal operations. This type of understanding could feed into condition monitoring systems and support the development of predictive maintenance. New Zealand company Seequent’s Leapfrog software is the current geothermal industry leader for geological and well modelling, with 90% of operational geothermal plants globally utilising it

Minimise Maintenance

Geothermal operations are extremely capital intensive, compared to other renewable options such as wind and solar, and so the return on investment is highly dependent on the operational efficiency and effectiveness. To improve the efficiency, geothermal operation must be maintained at optimum conditions and any unplanned events should be reduced to a minimum. As discussed, these plants, currently, have frequent maintenance events that can interrupt production.

There is an opportunity to transfer knowledge and expertise on predictive maintenance and asset management from the oil and gas industry into geothermal. Geothermal power and/or heat plants are complex operations that involve consideration of the subsurface conditions, reservoir conditions, as well topside power generation / heat exchange and distribution functions. The oil and gas industry is well placed to address these complex requirements, including for surface infrastructure such as heat network pipelines, although there is stiff competition from experienced incumbents such as companies in Denmark and Sweden.

Sensor Technology

As drilling becomes more complex, there is a need more information on the performance of the drilling operations in real time. Measurement-While-Drilling (or MWD) is a type of well logging that incorporates the measurement tools into the drill string and provides real-time information to help with steering of the drill. Providing wellbore position, drill bit information and directional data, as well as real-time drilling information, MWD uses gyroscopes, magnetometers and accelerometers to determine borehole inclination and azimuth during the actual drilling process. As geothermal operations move to deeper fields, there is a clear need for new instruments and devices that can operate a high temperatures and pressures.

4.3 Engineered Geothermal Systems

To effectively utilize EGS resources, an array of injection and production wells must be accurately placed to create the formation fracture network. This will result in requirements in the areas of

- Directional Drilling
- Real-time data and long-term monitoring
- Transfer of knowledge from shale gas fracking

Directional Drilling

EGS can greatly benefit from a high temperature, directional drilling system. Early demonstration projects have revealed that inclined wells are better for EGS than vertical wells. However, most commercial services for directional drilling systems are rated for 175°C while geothermal wells require operation at much higher temperatures.

For the EGS to make the most use of directional drilling techniques, systems need to be developed that can operate at higher temperature, above 200°C. As discussed earlier, for accurate drilling, data is required on drill position and its status which, in turn, requires more robust navigation and telemetry systems.

Real-time data and long-term monitoring

To maximise performance of EGS and, in fact, all geothermal technologies, reliable and long-term geothermal reservoir monitoring is required. This will include solutions that provide accurate information on reservoir stimulation, reservoir temperature evolution / sustainability, reservoir deformation due to changes in pressure and temperature, and fracture networks including flow distribution. A highly important requirement within EGS is the need for real-time monitoring of induced seismicity.

Distributed fibre optic sensors systems, for example, can be used for this purpose. The fibre optic cable can be cemented behind the casing to the reservoir depth to provide simultaneous and continuous measurement. However, the maximum operating temperature for fibre optic sensos is around 230°C. If geothermal operations are to tap into high temperature resources, new sensors will be required that can function beyond 250°C, at high pressure high pressure conditions and be reliable over a long period of time.

Transfer of knowledge from shale gas hydraulic stimulation

There is considerable opportunity to transfer knowledge, expertise and skills developed from shale gas hydraulic stimulation into EGS. In many cases, the two industries face similar challenges. For example, in both industries there is a need to drill boreholes as quickly and as accurately as possible. Novel drilling rigs were developed in shale gas fracking to speed up operations and these could be applied to EGS.

EGS is still in the development phase so there are funding issues that must be overcome. As discussed earlier, current geothermal projects, in general, focus on reducing capital expenditure and commencing revenue generation as soon as possible. It may be that shale gas fracking technologies are too costly for EGS at its current stage of development. SAGE Geosystems in Texas are innovation a single-well EGS system with highly sophisticated targeted hydraulic stimulation, and their team are predominantly veterans from the O&G industry[39].

4.4 Closed Loop Geothermal Systems

As introduced earlier, closed-loop geothermal (CLG) has several features that are attractive compared to EGS. It is a completely closed system with no fluid exchange within the geothermal reservoir and does not involve injection of fluid into rock to increase porosity. It also has the potential to be used as a retrofit technology to augment existing geothermal operations or to restart abandoned mines that became commercially unviable. We have identified the following opportunities within CLG for oil and gas companies:

- Complex and accurate directional drilling
- Use of advanced fluids
- Advanced turbines

Directional Drilling for Closed-Loop Geothermal

Closed-loop geothermal systems require advanced drilling techniques, including direction and horizontal drilling. As is apparent from the concept proposed by companies such as Eavor Technology, closed-loop systems can be very complex, involving the connection of two vertical wells, which could be several kilometres down, with many horizontal wellbores that could be several kilometres long.

The drilling requirement for this type of closed loop system is, clearly, very complex, with precise multilateral drilling required for the creation of very specific subsurface profiles.

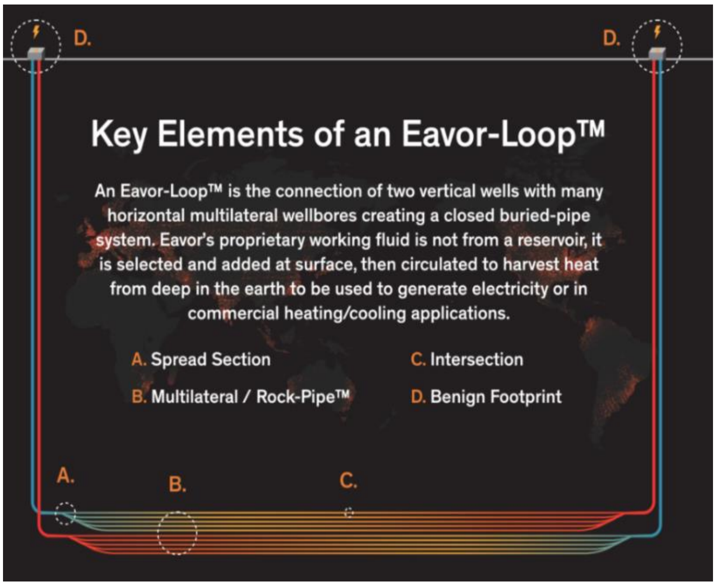

Figure 36: Key Elements of an Eavor-Loop

There is clearly an opportunity here for companies that can provide a means for very precise control of directional drilling, rotary steerable tools, and to enable sensing to measure position and drill condition while drilling.

As is the case with the other types of geothermal systems, these tools and instruments must operate at high temperatures (greater than 200°C) and at high pressures, under harsh conditions – although closed loop systems are being designed for low temperature heat networks

39 https://www.sagegeosystems.com/technology/

Use of Advanced Fluids

Unlike conventional geothermal, which uses water or brine as the means to transfer heat, closed loop systems can take advantage of advanced fluids, such as supercritical CO_2. A supercritical fluid (SCF) is any substance at a temperature and pressure above its critical point, where distinct liquid and gas phases do not exist. By using supercritical CO_2 as the working fluid to drive the electricity generating turbine, developers are attempting to increase the efficiency of the system. Using supercritical CO_2 as the working fluid means has more efficient heat exchange than water / brine with the reservoir / well and takes less work to convert a given amount of thermal input to electricity. Another benefit of using supercritical CO_2 to power turbines is that with its liquid-like density, the compressor needs less pumping power and, therefore, saves energy.

Using supercritical fluids in geothermal systems could lead to opportunities in the support of associated expertise and equipment. For example, compressors and turbines that are optimised for supercritical fluids. Also, there has been some exploration of the use of supercritical CO_2 in hydraulic fracturing. O&G companies who already implement CO2 enhanced oil recovery (EOR) will be well suited to entering this market.

Advanced turbines

A range of different turbines are used in geothermal systems, depending on the temperature of the geothermal resource, including dry steam, flash steam and binary cycle turbine operations. The efficiency of these systems, however, is low and, so, alternative generation systems are being explored. One such example is thermoelectric generators where thermoelectric materials can be used to directly covert heat into electricity, working with low temperature geothermal resources.

4.5 Abandoned Mines

There are four key technologies requirements for the exploitation of mine water as a geothermal resource:

- Accurate drilling – targeting a mine roadway of c. 2m width at several hundred meters depth is challenging, and existing water well drillers have not demonstrated competence so far, with exploration programmes at current UK schemes to identify open roadways holding very high costs.
- Heat exchangers – where mine water heat exchange is most likely to take place in a system, to avoid fouling of the more costly heat pumps. Shell & tube heat exchangers have been shown to be less susceptible to fouling than plate heat exchangers in mine water applications.
- Heat pumps – where heat from clean loop between the mine water heat exchanger is collected, then elevated with some electrical input for end use
- Heat networks – where the heat provided from heat pumps is carried to users via a network of insulated underground pipes

In terms of areas of need and potential opportunities, we would highlight the following:

- Modelling work to understand heat depletion
- Corrosion and fouling

Modelling

Greater understanding is required on what might constitute a sustainable heat yield. As discussed earlier, the risk of heat depletion over time is a major barrier to the exploitation of mine water as a geothermal resource. Improved modelling is required to better understand the mine water reservoir and the types of interactions that may occur, which could impact the heat resource.

Corrosion and Fouling

As with other types of geothermal systems there is the ever-present challenge of managing corrosion and fouling. High levels of dissolved minerals can foul heat exchangers, for example. Again, this is a site-specific issue and heat exchanger materials should be selected to take account of the water composition on scheme-by scheme basis.

4.6 Attractive Market Opportunities

From the analysis of technical challenges across the different geothermal operational types we have developed the following long list of market opportunities for the oil and gas companies that have been identified and are listed in the accompanying database:

- Well Engineering
    - Improved well structure (casing, tubulars, cementing etc.)
    - Directional drilling at high temperature and pressure (over 220°C)
    - New drill bit technology to support drilling down to 10km through various rock formations
    - Automated, fast drilling technology to support multi-well EGS
    - Improved pumping technology to support artificial lift
- Measurement and Control
    - Sensing technology to support measurement while drilling (high temp and pressure)
    - Sensing technology to support long term monitoring
    - Sensing technology to support flow assurance
    - Application of machine learning to support data analysis and performance improvement
    - Application of artificial intelligence to support improved process control
    - Application of predictive maintenance to support reduction of maintenance costs
- Modelling and Simulation
    - Improved subsurface and surface physical modelling to support reservoir characterisation and prediction of production
    - Improved modelling and simulations to support analysis of induced seismicity
- Power Generation
    - Development of new turbines to support closed loop geothermal
    - Optimisation of topside operation to increase power conversion efficiency
- Corrosion
    - Corrosion and scaling prevention and maintenance

The commentary on the technical challenges in the different types of geothermal energy in the sections above highlights that a number of these opportunities relate to more than one geothermal energy application. This is summarised in the figure below. In this figure ●●● indicates a strong alignment,

●● a medium alignment, and ● a weak alignment of the market opportunities with the different types of geothermal operation.

	Market Opportunity	Type of Geothermal				Regional Applicability
		Traditional	Deep Geo	EGS	Closed Loop	
Well Engineering	Improved well structure (casing, tubulars, cementing etc.)	●●●	●●●	●●●	●●●	All regions
	Directional drilling at high temperature and pressure (over 220°C)	●	●	●●	●●●	USA, Europe
	New drill bit technology to support drilling down to 10km through various rock formations	●	●●●	●●	●	USA, Europe
	Automated, fast drilling technology to support multi-well EGS	●	●	●●●	●●	USA
	Improved pumping technology to support artificial lift	●●●	●●●	●●	●●	All regions
Measurement and Control	Sensing technology to support measurement while drilling (high temp and pressure)	●	●●●	●●●	●●●	USA, Europe
	Sensing technology to support long term monitoring	●●●	●●●	●●●	●●●	All regions
	Sensing technology to support flow assurance	●●●	●●●	●●●	●●●	All regions
	Application of machine learning to support data analysis and performance improvement	●	●●	●●●	●●●	USA, Europe
	Application of artificial intelligence to support improved process control	●	●●	●●●	●●●	USA, Europe
	Application of predictive maintenance to support reduction of maintenance costs	●	●●●	●●●	●●●	USA, Europe
Modelling and Simulation	Improved subsurface and surface physical modelling to support reservoir characterisation and prediction of production	●●	●●●	●●●	●●●	All regions
	Improved modelling and simulations to support analysis of induced seismicity	●	●	●●●	●●	All regions
Corrosion	Corrosion and scaling prevention and maintenance	●●●	●●●	●●●	●●●	All regions
Power Generation	Development of new turbines to support closed loop geothermal	●	●	●	●●●	USA, Europe
	Optimisation of topside operation to increase power conversion efficiency	●●●	●●●	●●●	●●●	All regions

Figure 37: Alignment of Opportunities by Geothermal Type

This shows that

- Some technology opportunities, such as improved well structure casing, is an important issue for almost all geothermal types (the only exception being abandoned mine water).
- Similarly sensing is an important requirement across all well types and the application of artificial intelligence to improve process control and predictive maintenance to support the reduction of maintenance costs is a growing requirement that is important across all geothermal types.
- Some opportunities are more applicable to certain geographic markets. For example, the US is very active in the exploration of EGS, transferring and building on the knowledge and expertise developed in shale gas fracking.

This figure, therefore, highlights that specific opportunities, e.g. improved well structure (casing, tubulars, cementing etc.), exist in different geothermal energy projects, which are under development in numerous geographic markets. This suggests potentially large global markets for oil and gas companies entering the geothermal sector.

4.7 Aligning Opportunities with Capability

Analysis of the alignment of the opportunities with the oil and gas capability categories detailed in Section 2 is summarised in the figure below.

	Market Opportunity	Well Engineering					Data					Corrosion				
		Well drilling	Well testing	Drilling and completion engineering	Support services	Well components / systems	Data collection	Data communication	Data management	Data analytics	Visualisation	Surface engineering eg coatings/galvanising	Corrosion control eg cathodic protection/inhibitors	Corrosion monitoring eg NDT etc	Subsurface modeling	Other
Well Engineering	Improved well structure (casing, tubulars, cementing etc.)	•	•	•	•	•	•					•	•	•		
	Directional drilling at high temperature and pressure (over 220°C)	•	•	•			•									
	New drill bit technology to support drilling down to 10km through various rock formations	•			•	•										
	Automated, fast drilling technology to support multi-well EGS	•			•	•										
	Improved pumping technology to support artificial lift					•										
Measurement and Control	Sensing technology to support measurement while drilling (high temp and pressure)						•	•	•	•						
	Sensing technology to support long term monitoring						•	•	•	•	•					
	Sensing technology to support flow assurance						•	•	•							
	Application of machine learning to support data analysis and performance improvement									•	•					
	Application of artificial intelligence to support improved process control									•	•					
	Application of predictive maintenance to support reduction of maintenance costs									•	•					
Modelling and Simulation	Improved subsurface and surface physical modelling to support reservoir characterisation									•	•				•	
	Improved modelling and simulations to support analysis of induced seismicity									•	•				•	
Power Generation	Development of new turbines to support closed loop geothermal															•
	Optimisation of topside operation to increase power conversion efficiency															•
Corrosion	Corrosion and scaling prevention and maintenance											•	•	•		

Figure 38: Alignment of Opportunities by Oil and Gas Capability

This analysis shows that, within the domain of well engineering, there is good alignment between geothermal opportunities and oil and gas capability in the areas of well drilling, drilling and completion engineering and well components. In the data domain, there is good alignment with data collection and data analysis. There is also good alignment in corrosion / fouling control and corrosion / fouling monitoring, as well as with subsurface modelling.

It should be noted that the above analysis provides an indication of geothermal opportunity alignment to the oil and gas industry capability categories we assessed as part of this study. It does not align directly to company capability is each of these categories.

4.8 Attractiveness and Prioritisation

All the long-listed opportunities offer good supply chain potential for Scottish oil and gas companies. The attractiveness of each opportunity to a potential supplier will depend on the specific capability of that supplier and their specific market diversification strategies and preferences. However, in order to select opportunities for which to develop profiles we have conducted further prioritisation by scoring each opportunity against three criteria:

- Opportunity Attractiveness
    - Unmet need (critical challenge) – is there strong current demand and the degree to which the opportunity is a critical issue for the geothermal industry?
    - Scale of the opportunity - is the market large and is the opportunity applicable across different geothermal types?

  - Long-term market growth – is there strong, long term growth potential for the opportunity?
  - Competitor activity – is there strong, existing competition within this domain?
  - Route to market – how accessible is the market opportunity for new entrants?
- Scottish Capability Fit
  - Relevant Scottish capability – there are Scottish based oil and gas companies identified that have relevant capabilities to pursue these opportunities
  - Time to access – the track record of companies, in terms of innovation and new product/service development, indicates that they would be able to develop the specific capability to access markets in a relatively short period of time
  - Ability to access international markets – identified companies have a track record of international market development, either directly or through sister companies within their group
- Strategic Fit
  - Aligns well with Scottish Government Policy – industrial, environmental, and social
  - Links to key Scottish Sectors – a key industrial activity or emerging area of excellence

For each criteria a score of High (5), Medium (3) or Low (1) was allocated, based on our understanding of the opportunity and of relevant Scottish capability. As an example, we describe the scoring process for the first opportunity below:

Market Opportunity:	Improved well structure (casing, tubulars, cementing etc.)
Opportunity Attractiveness*:*	Improving well casing and cementing is a critical need – score high, 5 The opportunity is applicable to all geothermal well types (less applicable in mine water geothermal) –score high, 5 The long-term growing potential is good, but as scale is reached, standardised solutions are expected to be the norm – score medium, 3 The are many oil and gas companies offering well casings and similar services, so competition is strong – score low, 1 New entrants will find it difficult to enter a crowded market and differentiate themselves – score low, 1
Scottish Capability Fit:	Numerous (over 15) companies were identified with relevant capability – score high, 5 Numerous companies already experienced in providing well design and construction for different environment – score high, 5 Many of the relevant companies already have an international presence – score high, 5
Strategic Fit:	As this is a core oil and gas activity, supporting companies in this domain to diversify fits strongly with government policy – score high, 5 This is a key industrial activity in Scotland, where companies have considerable expertise - score high, 5

The full scoring matrix is as follows:

	Market Opportunity	Opportunity Attractiveness					Scottish Capability Fit			Strategic Fit		Opportunity Score
		Unmet need (critical challenge)	Scale of the opportunity	Long-term market growth	Competitor activity	Route to market	Relevant Scottish Capability	Time to Access	Ability to Access International Markets	Aligns well with Scottish Govermment Policy	Link to Key Scottish Sectors	
Well Engineering	Improved well structure (casing, tubulars, cementing etc.)	5	5	3	1	1	5	5	5	5	5	40
	Directional drilling at high temperature and pressure (over 220°C)	3	3	5	3	3	3	1	5	5	5	36
	New drill bit technology to support drilling down to 10km through various rock formations	3	1	3	3	3	3	3	5	5	5	34
	Automated, fast drilling technology to support multi-well EGS	1	3	5	3	3	1	1	5	1	3	26
	Improved pumping technology to support artificial lift	5	5	3	1	1	1	5	5	3	3	32
Measurement and Control	Sensing technology to support measurement while drilling (high temp and pressure)	3	3	5	3	3	3	3	5	5	5	38
	Sensing technology to support long term monitoring	5	5	5	3	3	5	5	5	5	5	46
	Sensing technology to support flow assurance	5	5	5	3	3	3	3	5	5	5	42
	Application of machine learning to support data analysis and performance improvement	1	1	5	5	3	3	3	3	5	5	34
	Application of artificial intelligence to support improved process control	1	1	5	5	3	5	3	3	5	5	36
	Application of predictive maintenance to support reduction of maintenance costs	3	3	5	3	3	3	3	3	5	5	36
Modelling and Simulation	Improved subsurface and surface physical modelling to support reservoir characterisation and prediction of production	5	5	3	1	3	5	3	5	3	5	38
	Improved modelling and simulations to support analysis of induced seismicity	3	3	3	1	3	3	3	3	3	5	30
Corrosion	Corrosion and scaling prevention and maintenance	5	5	3	3	3	5	3	5	5	5	42
Power Generation	Development of new turbines to support closed loop geothermal	3	1	3	1	1				3	3	
	Optimisation of topside operation to increase power conversion efficiency	5	5	3	1	3				5	3	

Figure 39: Market Opportunity Prioritisation

Note: The last two opportunities on the list could not be fully scored as they did not align with Scottish capability.

This assessment shows that several opportunities achieved similar scores, indicating similar attractiveness and supply chain potential.

4.9 High Priority Opportunities

As part of our methodology, we have identified those opportunities that scored highest in this analysis, as follows:

	Market Opportunity	Opportunity Attractiveness					Scottish Capability Fit			Strategic Fit		
		Unmet need (critical challenge)	Scale of the opportunity	Long-term market growth	Competitor activity	Route to market	Relevant Scottish Capability	Time to Access	Ability to Access International Markets	Aligns well with Scottish Government Policy	Link to Key Scottish Sectors	Opportunity Score
Measurement and Control	Sensing technology to support long term monitoring	5	5	5	3	3	5	5	5	5	5	**46**
Measurement and Control	Sensing technology to support flow assurance	5	5	5	3	3	3	3	5	5	5	**42**
Corrosion	Corrosion and scaling prevention and maintenance	5	5	3	3	3	5	3	5	5	5	**42**
Well Engineering	Improved well structure (casing, tubulars, cementing etc.)	5	5	3	1	1	5	5	5	5	5	**40**
Measurement and Control	Sensing technology to support measurement while drilling (high temp and pressure)	3	3	5	3	3	3	3	5	5	5	**38**
Modelling and Simulation	Improved subsurface and surface physical modelling to support reservoir characterisation and prediction of production	5	5	3	1	3	5	3	5	3	5	**38**

Figure 40: High Scoring Opportunities

Opportunity profiles have been developed for these high scoring opportunities as shown in Appendix C, where the description of the three sensing technology opportunities have been combined into one opportunity profile.

4.10 Attractive Geographic Markets

Our analysis has highlighted the global nature of the development of geothermal energy and the different geographies and geothermal energy operations where attractive market opportunities arise. It is recognised, however, that there needs to be a more targeted focus on specific geographic (i.e. country) market opportunities to support company business development activities. We have, therefore, identified the following geographic markets as priorities to target.

1. Turkey

Geothermal Operation: Energy generation
Direct heat use

Rationale: Largest European market
Significant growth predicted
Extended feed-in tariffs to support growth
Several key oil and gas players already active

Key market opportunities:	Improved well structure (casing, tubulars, cementing, etc.) Corrosion and scaling prevention to lower maintenance costs Sensing technology to support measurement while drilling (high temp and pressure) Sensing technology to support long term monitoring Sensing technology to support flow assurance Optimisation of topside operation to increase power conversion efficiency Improved subsurface and surface physical modelling to support reservoir characterisation and prediction of production

2. Germany

Geothermal Operation:	Direct heat use
Rationale:	Strong government support for renewable energy Good growth predicted Emerging supply chain
Key market opportunities:	Improved well structure (casing, tubulars, cementing, etc.) Sensing technology to support long term monitoring Sensing technology to support flow assurance Improved pumping technology to support artificial lift Improved subsurface and surface physical modelling to support reservoir characterisation and prediction of production

3. Indonesia

Geothermal Operation:	Energy generation
Rationale:	Largest natural geothermal resource in the world Projected to become the largest global market for power generation Significant geothermal investment plan by the Indonesian government
Key market opportunities:	Improved well structure (casing, tubulars, cementing, etc.) Corrosion and scaling prevention to lower maintenance costs Sensing technology to support long term monitoring Sensing technology to support flow assurance Improved subsurface and surface physical modelling to support reservoir characterisation and prediction of production

4. USA

Geothermal Operation:	Energy generation Direct heat use
Rationale:	Currently, the largest market for geothermal power generation Strong pipeline of projects Expected to be global leader in advanced geothermal systems Strong ongoing support and funding from US government
Key market opportunities:	Improved well structure (casing, tubulars, cementing, etc.) Corrosion and scaling prevention to lower maintenance costs Directional drilling at high temperature and pressure (over 220°C) Automated, fast drilling technology to support multi-well EGS

Sensing technology to support measurement while drilling (high temp and pressure)
Sensing technology to support long term monitoring
Sensing technology to support flow assurance
Application of predictive maintenance to support reduction of maintenance costs
Improved subsurface and surface physical modelling to support reservoir characterisation and prediction of production
Improved modelling and simulations to support analysis of induced seismicity

5 Conclusions and Recommendations

5.1 Conclusions

This study has assessed the expected growth in geothermal markets and identified potential opportunities for oil and gas supply chain companies with expertise in well engineering, sub surface modelling, corrosion mitigation and data. Based on the analysis carried out we have come to the following conclusions.

1. There is a significant base of oil and gas supply chain companies with capabilities which offer the potential for diversification into the geothermal supply chain. Almost 220 oil and gas companies with the potential to diversify were identified, segmented as follows:
   - Well engineering 131 companies
   - Sub-surface modelling 15 companies
   - Corrosion mitigation 25 companies
   - Data 46 companies

   Further, a significant number of these companies have demonstrated the potential to innovate and / or to access international markets
2. The geothermal energy market offers attractive diversification opportunities
   It is already established, with significant growth demonstrated over the last 10 years. It is estimated that:
   - Europe has an installed geothermal electricity capacity of 3.5GWe in 2020, distributed over 139 power plants
   - There were 350 geothermal district heating systems in operation in Europe in 2020 and a further 232 were in various stages of development

   It is expected to grow significantly over the period to 2050. For example,
   - Geothermal electricity generation, including engineered geothermal systems, is expected to grow by a factor of ten over the period from 2020 to 2050
   - Geothermal direct use is predicted to grow by a factor of six over the same period

   The largest geothermal electricity generation markets are the USA, Indonesia, the Philippines and Turkey, with all these countries having large portfolios of planned projects
3. Geographic geothermal markets are dependent on the specific geological conditions in different regions. As a result, similar geological conditions are being exploited in similar ways in different regions, leading to similar opportunities in these regions.
4. The geothermal sector has several technical challenges to address as it continues to grow and maximise output, namely:

Conventional Geothermal	Deep Geothermal	Engineered Geothermal Systems	Closed Loops Geothermal Systems	Abandoned Mines
Well structure failure	New drilling techniques	Directional Drilling	Complex and accurate directional drilling	Modelling to understand heat depletion
Corrosion and scaling	New tools	Real-time data and long-term monitoring	Use of advanced fluids	Corrosion and fouling
High flow rates	Improved modelling and simulation	Transfer of knowledge from shale gas fracking	Advanced turbines	
Failure of pumps	Minimise maintenance			
Integrated design	Improved sensors			

5. Sixteen specific areas of opportunity for Scottish oil and gas companies were identified through analysis of these technical challenges. The opportunities that are considered to be most attractive are:

- Improved well structure (casing, tubulars, cementing etc.)
- Corrosion and scaling prevention and maintenance
- Sensing technology to support measurement while drilling (high temp and pressure)
- Sensing technology to support long term monitoring
- Sensing technology to support flow assurance
- Improved subsurface and surface physical modelling to support reservoir characterisation and prediction of production

6. Priority geographic markets for Scotland to pursue these opportunities, based on current activities, future growth and need for new technologies are Turkey, Indonesia, the USA and Germany.
7. A number of the major oil and gas sector companies, such as Baker Hughes and Schlumberger are already active in geothermal markets and could offer market access.

5.2 Recommendations

Based on the work carried out in this study it is recommended that:

- Scottish oil and gas companies are encouraged to pursue geothermal market opportunities
- The priority markets identified above should be pursued in the first instance
- More in-depth analysis of specific opportunities is carried out to support Scottish companies to pursue these
- Access to a database of developing and new geothermal projects and contracts is established to identify forthcoming opportunities for Scottish companies
- Market access mechanisms, through a range of linkages, including diversified oil and gas companies and national renewable energy organisations are developed

Appendices

Appendix A – Company Database

The company database is provided as a separate document entitled Scottish Enterprise Geothermal Supply Chain Companies.xlsx.

Appendix B – Key Geothermal "Plays"

(1) Volcanic Field Type

Dominant Geothermal Type	Tectonic Setting	Examples	Countries/Territories	Brief Description	Main Technical Challenges
Volcanic Field Type	Hot spot	Hawaii	USA	Magma body, chamber, intrusion, centrally located between/below a continental or oceanic plate, usually with a very deep source supplying a plume	Complex geology, limited data, location access, permeability, steam blowouts. Infrastructure resiliance to volcanic eruptions (eg. Kilauea East Rift eruption 2018, and Puna Geothermal). Heat flow at hotpots can be unpredictable due to advective heat loss and fluid flow. Elevated risk of corrosion where reservoir recharge source is seawater
		Le Reunion	France		
		St. Helena	UK		
		São Tomé and Principe	Portugal		
	Mid-ocean ridge	Reykjanes	Iceland		
		Ascension	UK		
		Tristan de Cuhna			
		Azores	Portugal		
		Galapagos	Ecuador		
	Magmatic Arc - Continental Arc	Cascade Volcanic Arc	USA	Subduction of a water saturated oceanic plate beneath another. Increased pressure with depth squeezes water out, introducing the water to the mantle. Water lowers the melting point of the mantle, melting it to form magma which ascends to the surface with increased bouyancy, forming volcanic centres at the centre.	Many locations are difficult to access for both exploration and exploitation purposes. Often located in proximity to areas at risk of natural hazards, therefore infrastructure reiliance to natural hazards. Magmatic advection is the dominant heat transport mechanism - heat can be transported a distance away from the percieved source increasing the likelihood of a blind resource 10's to 100's km away and an unpredictable or low heat flow at the perceived source.
		Alaska Peninsula & Aleutian Range			
		Kamchatka	Russia		
		Andes (North)	Colombia		
			Equador		
			Peru		
		Andes (Central)	Bolivia		
			Chilie		
		Andes (Southern)			
		Andes (Austral)	Patagonia		
		Central America Volcanic Arc	Mexico		
			Guatemala		
			El Salvador		
			Nicaragua		
			Costa Rica		
			Panama		
	Magmatic Arc - Island Arc	Aleutian Islands	USA		If there is a poor undersatnding of geology, heat flow, controls on fluid flow, hydrostatic conditions, and system phases, the high temperature at relatively shallow depths can see increased occurences of steam blowouts and string kick backs. Permeability can be mixed and relies considerably on cooling joints and fractures certainly in the shallower systems. Locations proximity to tectonic structures will determine deeper permeability. Increased risk of corrosion where reservoir recharge has a high seawater content.
			Russia		
		Kuril Islands	Russia		
		Northeastern Japan Arc	Japan		
		Japanese Archipelago (inc. Ryuku Islands)			
			Russia		
		Izu-Bonin-Mariana Arc (Izu, Bonin, Mariana Islands)	Japan		
			USA overseas territory		
		Luzon Volcanic Arc	Philippines		
		Philippines			
		Tonga & Kermadec Islands	Polynesia		
			New Zealand		
		Andaman & Nicobar Islands	India		
			Myanmar		
		Mentawai Islands	Indonesia (West Sumatra)		
		Sunda Arc (Lesser Sunda Islands)	Indonesia (Sumatra, Nusa Tenggara, Java (inc. Sunda Strait, Lesser Sunda Islands))		
		Tanimbar & Kai Islands	Indonesia		
		Solomon Islands	Solomon Islands (Papua New Guinea)		
		Aeolian Islands	Italy		
		South Agean Volcanic Arc & Hellenic Arc	Greece		
		Lesser Antilles (inc. Leeward Antilles)	Carriacou		
			Dominica		
			Grenada		
			Martinique (France)		
			Petite Martinique		
			Saint Lucia		
			Saint Vincent		
			Antigua & Barbuda		
			Guadeloupe (France)		
			Saint Kitts & Nevis		
			Saint Martin (France, Netherlands)		
			Virgin Islands (UK, USA)		
			Montserrat (UK)		
			Anguilla (UK)		
			Saint Barthelemy (France)		
			Saba (Netherlands)		
			Sint Eustatius (Netherlands)		
			ABC Islands (Netherlands)		
			State of Nueva Esparta (Venezuela)		
			Islands of La Tortuga		
			La Sola		
			Los Testigos		
			Los Frailes		
			Patos		
			Blanquilla		
			Orchila (Venezuela)		
			Archipelagos of Los Monjes		
			Los Roques		
			Los Hermanos		
			Las Aves (Venezuela)		
		Scotia Arc	South Sandwich Islands (UK)		
		Mascarene Islands	Mauritius		

(2) Plutonic Type

Dominant Geothermal Type	Tectonic Setting	Examples	Countries/Territories	Brief Description	Main Technical Challenges
Plutonic Type	Batholliths	Aswan Granite	Egypt	Intrusion of a large volume of igneous material, larger than 100 km^3. Felsic to intermediate chemsitry (granite, quartz monzonite, diorite). Magma migration associated with underplating and partial melting, forming plutonic diapirs before rising and cooling between 5-30 km below the surface - only exposed over time with erosion.	Geologically complex. Heat flow can vary significantly due to concentrations and segregation of radiogenic minerals. Permeability relies entirely on the degree of fracturing which often requires stimulation/EGS. There is no primary porosity - no storativity with the exception of that wihin open fractures. Usually requires fluid injection to generate a power output
		Cape Coast	Ghana		
		Paarl Rock	South Africa		
		Darling			
		Hook Granite Massif	Zambia		
		Mubende	Uganda		
		Antarctic Peninsula	Antarctica		
		Queen Maud			
		Angara-Vitim	Siberia		
		Bongir Fort	India		
		Chibagalakh	Siberia		
		Mount Abu	India		
		Gangdese	Himalaya		
		Trans-Himalayan Batholith			
		Karakorum Batholith			
		Kalba-Narym	Kazakhstan		
		Tak	Thailand		
		Tien Shan	Central Asia		
		Ranchi	India		
		Bindal	Norway		
		Cornubian	England		
		Corsica-Sardinia			
		Donegal	Ireland		
		Leinster			
		Mancellian	France		
		North Pennine	England		
		Ljusdal	Sweden		
		Mt-Louis-Andorra	Spain		
		Riga	Latvia		
		Salmi	Russia		
		Sunnhordaland	Norway		
		Transscandinavian Igneous Belt	Sweden & Norway		
		Vitosha - Plana	Bulgaria		
		Bald Rock	USA		
		Boulder			
		Chambers-Strathy			
		Chilliwack			
		Golden Horn			
		Idaho			
		Kenosha			
		Liberty Bell Mountain			
		Peninsular Ranges			
		Pike's Peak Granite			
		Ruby Mountains			
		Sierra Nevada Batholith			
		Stone Mountain			
		Town Mountain Granite			
		Wyoming			
		Median Batholith	New Zealand		
		Cullen	Australia		
		Kosciuszko			
		Moruya			
		Scottsdale			
		New England			
		Achala Batholith	Argentina		
		Cerro Aspero			
		Colangüil			
		Antioquia	Colombia		
		Parguaza rapakivi granite	Venezuela and Colombia		
		Coastal	Peru		
		Cordillera Blanca			
		Vicuña Mackenna	Chile		
		Futrono-Riñihue			
		Coastal			
		Panguipulli			
		Illescas Batholith	Uruguay		
		Guanambi	Brazil		
		Elqui-Limarí	Chile and Argentina		
		Patagonian			
		British Virgin Islands	UK		
		Ilimaussaq	Greenland		
		Rio Verde	Mexico		
		South Mountain	Canada		
	Laccoliths	Torres del Paine	Patagonia	A shallow dome intrusion usually assocaited with concordant plutons. Injected into points of weakness within or between sedimentary units (a cryptodome where the country rock is volcanic). Greater intrusion pressure results in doming as opposed to sills that do no form domes and have a lower intrustion pressure.	Technial challenges are very similar to theose of batholliths. Additional challenges relate to the size in that they are much smaller and the shape could easily result in a missed target with inadequate data.
		Barber Hill	USA		
		Solitario			
		Pine Valley Mountain			
		Notch Peak			
		Vitosha - Plana	Bulgaria		
	Lopoliths	Sudbury Igneous Complex	Canada	Large, lenticular intrusion with a depressed centre. Form over a significant period of time and often consist of layered intrusions that can differ in age from Archean to Eocene.	Similar technical issues to laccoliths and batholliths with the added risk of a very costly development program resulting in no heat flow as itsformation age means there is very little radiogenic decay of minerals remaining and heat at best is residual.
		Bushveld Igneous Complex	South Africa		
		Great Dyke	Zimbabwe		
		Skaergaard Complex	Greenland		

(3) Extensional Domain Type

Dominant Geothermal Type	Tectonic Setting	Examples	Countries/Territories	Brief Description	Main Technical Challenges
Extensional Domain Type	Intracontinental rift (active)	East African Rift System (EARS) - Eastern Branch	Kenya	Fault controlled - plates pull apart (divergent plate boundary), crustal thinning, elevated heat flow at the surface, convection dominated heat transfer, rift border faults inactive, intra-rift faults act as permeability zones for fluid migration (groundwater, magma, brines)	Poor knowledge of geological setting, significant circulation losses, that while indicating excellent permeability, can be problematic. Poor undersatnding of nature of reservoir recharge - risk of unsustainable development. Loss of drill string infrastructure - lack of knowledge on active magma migration. Limited data availability, where data does exist the quality is either poor or inaccessible out with the project (data sharing an issue)
			Ethiopa		
			Tanzania		
		East African Rift System (EARS) - Western Branch Branch	Ethiopia		
			Uganda		
			DRC		
			Rwanda		
			Burundi		
			Tanzania		
			Malawi		
			Mozambique		
	Intracontinental rift (failed)	Rhine Valley	Germany		Heat flow is often lower than that observed at active rifting centres. Permeability can be varied and depends on the age of the structures, time passed for fluid flow, mineral precipitation and fault sealing under natural state conditions. Likely to require manual stimulation/EGS. Porosity can also be an issue where sediments have become buired and with that compacted. Drilling challenges where granite has a role. Infrastructure resiliance (eg locations close to seismically active areas)
			France		
		Oslo Graben	Norway		
		Central Lowlands	Scotland		
		Worcester Basin	England		
		Central Graben, Viking Graben	North Sea		
		Vättern	Sweden		
		Lucapa Graben	Angola		
		Lambert Graben	Antarctica		
		Narmada River Valley, Godavari River Valley	India		
		Baikal Rift Zone, Moma Graben	Russia		
		Büyük Menderes Graben	Turkey		
		Unzen	Japan		
		Guanabara Graben	Brazil		
		Firth of Thames (inc. Hauraki Graben)	New Zealand		
		Gulf St. Vincent	Australia		
		Tamar Valley	Australai		
		Eastern North America Rift Basins	Canada		
			USA		
		Midcontinent Rift Systsem	Canada		
			USA		
		Salton Trough	Mexico		
			USA		
		Ottawa-Bonnechere Graben, Saguenay Graben	Canada		
		Basin and Range Provine (inc. Death Valley, Salt Lake Valley, Owens Valley), Lake george Basin, Lake Tahoe Basin, Republic Graben, Rio Grande Rift Valley, Rough Creek Graben, Santa Clara Valley, Western Snake River Plain	USA		
		Guatemala City Valley	Guatemala		
	Pull-apart Basins	Salton Sea	USA	A pull apart basin is a structuarl basin where two en-echelon strike-slip faults and fault bends create an area of crustal extension under conditions of tension that leads to localised subsidence. Felsic intrusions, complex fault networks, increased heat flow and varied fluid flow, make these structures targets for geothermal and mineral exploration and exploitation.	Strutural complexity and varied lithologies can make for drilling challenges, high risk of circulation losses, and unexpected sub-surface geology.
		Dead Sea	Isreal		
			Jordan		
		Vienna Basin	Austria		
		Escondida	Chile		
		Cariaco Basin	Venezuela		
		Cayman Trough	UK		
		Cocinetas Basin	Colombia		
		Los Angeles Basin	USA		
		Owambo Basin	Namibia		
		Yinggehai Basin	China		
	Metamorphic core complexes	Western Carpathians	Slovakia	Exposures of deep crust exhumed in association with amagmatic extensional processes. They form, and are exhumed in association with the rapid transport of of mid- and lower continental crust to the earth's surface. High-grade metamorphic rocks are formed, contiaining minerals that release radiogenic heat over long time scales.	Drilling challenges similar to granite with respect to rock/mineral hardness. Low angle, normal detachment faults provide relatively shallow fluid flow compensated by high heat flow associated with exhumation and a locally shallow Moho. With the exception of detachement faults, permeability throughout MCC's can be low and may require stimulation/EGS intervention
		Eastern Alps	Austria		
		Fosdick Mountains	Antarctica		
		Agean Sea	Greece/Turkey		
		Nigde Massif	Turkey		
		Saghand	Iran		
		The Kangmar Dome	Tibet		
		Bayankala Mountain, Xiaoqinling, Liaodong, Liaonan/Wanfu, Sulu	China		
		Cordillera de la Costa	Venezuela		
		Northern Ranges	Trinidad		
		Montagne Noire	France		
		Paparoa	New Zealand		
		D'Entrecasteaux Islands	New Guinea		
	Back-arc Basin	Tyrrhenian Sea	Current active extensional back-arc basins are all off shore. There are several fossil BAB's but it's unlikely they will provide a suitable heat flow unless accompanied by other plays as the dominant type.	Sub-marine, extensional basins associated with island arcs and subduction zones. The also develop in assocation with convergent plate boundaries behind magmatic arcs, forming under tensional condutions and oceanic trench roleback	Active BAB's are off-shore and would only be worth exploring where they could be utilised for power production as electricity transport is less likely to result in power losses as opposed to heat transport over distances. However with this comes the proximity to a power market, the required infrastructure for transport. Additional challenges include depth to ocean
		Okinawa Trough			
		Andaman Sea			
		Mariana Trough			
		Manus Basin			
		North Fiji Basin			
		Lau Basin			
		East Scotia Sea			

(4) Intracratonic Basin Type

Dominant Geothermal Type	Tectonic Setting	Examples	Countries/Territories	Brief Description	Main Technical Challenges
Intracratonic Basin Type	Intracratonic/rift basin	Paris Basin	France	Cratons are stable parts of the lithosphere found within larger tectonic plates. Intracratonic basins are sites of prolonged, broadly distributed but slow subsidence of the continental lithosphere. Commonly filled with terrestrial sediment accumulation and water, they have high porosity and storativity capabilities	As intracratonic basins are not associated with tectonic structures. Permeability is often lacking and requires stimulation/EGS. Heat flow can be varied, but generally greater in centrally located
		Ngalia Basin	Australia		
		Paraña Basin	Brazil		
			Paraguay		
			Argentina		
			Uruguay		
		Rub' al Khali Basin	Saudi Arabia		
		Illinois Basin	USA		
		Michigan Basin			
		Williston Basin			
		Hudson Bay			
		Western Canada Sedimentary Basin	Canada		
		Athabasca Basin			
		Vendian Basin	Russia		
		Moscow Basin			
		Mezen Basin			
	Passive margin basins (volcanic margins)	The Red Sea Margin	Yemen	Forms by sedimentation above ancient rifts. They are marked by transitional lithosphere, where crustal characteristics are transitional between oceanic and continental. The ancient margins are no longer tectonically active . They initially start as continental rifts, evolving to mid-ocean ridges. Passive margins are palaeo-rifts that have migrated away from the spreading centre over time. Non-volcanic margins form with extension and little input from mantle melting, volcanic margins form in assocaition with with LIP's and the emplacement of large volumes af mafic intrusive and extrusive igneous material over short periods of time. Rifting is accompanied by significant mantle melting.	The main technical challenges are very similar to BAB's in that they are off shore and would require significant infrastructure development for power transport and the identification of appropriate onshore markets where they are located in under-populated areas.
			Saudi Arabia		
		The Gulf of Aden Margin	Yemen		
		The East Australian Margin	Australia		
		The West Indian Margin	India		
			Pakistan		
		The Hatton-Rockal Margin	UK		
		The U.S. East Coast	USA		
		The mid-Norwegian Margin	Norway (inc. Svalbard)		
			The Faroe Islands		
			UK		
		The Brazilian Margins	Brazil		
			Uruguay		
		The Namibian Margin	Namibia		
			South Africa		
			Angola		
		The East Greenland Margin	Greenland		
		The West Greenland Margin	Greenland		
			Canada		
		The Moroccan Margin	Morocco		
			Western Sahara		
			Canary Islands		
			Cape Verde		
		The East African Margin	South Africa		
			Mozambique		
			Tanzania		
			Kenya		
			Somalia		
			Madagascar		
			Comoros		
			Mayotte (France)		
	Passive margin basins (non-volcanic margins)	Nova Scotia	Canada		
		West African **M**argin	Camaroon		
			Equatorial New Guinea		
			Nigeria		
			Gabon		
			Republic of the Congo		
		Portugese Margin	Morocco		
			Portugal		
		The Oman Margin	Oman		
		The South Australain Margin	Australia		

(5) Orogenic Belt Type

Dominant Geothermal Type	Tectonic Setting	Examples	Countries/Territories	Brief Description	Main Technical Challenges
Orogenic Belt Type	Fold & Thrust Belt (collisional orogen)	Atlas Mountains	Morocco	Mountains adjacent to an orogenic belt which forms with contractional deformation at convergent plate boundaries. Collisional orogens are found at continent-continent convergent plate boundaries, non-collisional orogens are found at ocean-continent convergent plate boundaries.	These regions have been largely avoided by oil and gas for exploration. Structurally, very complex. Geological structures (faults) will aid permeability and recharge, however the large basement fold structures could transport heat and fluid vertically downwards away from the surface area target, and beyond the depth of current exploitation well capabilities. Fluid and heat could also be transported towards the surface, but away from the percieved target area - blind resource. Complex folding with large wavelengths could also distribute a resource over very large areas adding to the challenges of resource identification , potential, and application.
			Algeria		
			Tunisia		
		The Appennines	Italy		
		The Alps	Italy		
			France		
			Switzerland		
			Austria		
			Liechtenstein		
		The Carpathians	Czech Republic		
			Poland		
			Austria		
			Slovakia		
			HungaryUkraine		
			Romania		
			Serbia		
		Dinaric Alps	Croatia		
			Bosnia & Herzogovnia		
			Montenegro		
		Balkan Mountains	Bulgaria		
		Sar Mountains	North Macedonia		
		Pindus & Rhodope Mountains, The Cyclades	Greece		
		Caucasus Mountains	North Turkey		
			Georgia		
			Russia		
			Azerbaijan		
			Armenia		
			North Iran		
		Zagros Mountains	Iraq		
			South Iran		
			South Turkey		
		The Himalayas	India		
			Pakistan		
			Afghanistan		
			China		
			Bhutan		
			Nepal		
		The Arakan Range	Myanmar		
			Thailand		
		Barisan Mountains	Sumatra		
	Fold & Thrust Belt (North American Cordillera) (non-collisional)	Basin & Range	USA		
			Mexico		
		Canadian Rockies	Canada		
	Fold & Thrust Belt (South Ameriacn Cordillera) (non-collisional)	Andes	Venezuela		
			Colombia		
			Ecuador		
			Peru		
			Bolivia		
			Chile		
			Argentina		
	Foreland Basin (peripheral)	Ganges	Himalaya	Occur adjacent and parallel to mountain belts. From associated with the huge mass created by crustal thickening associated with mountain building. Crustal mass causes the lithosphere to bend - lithospheric flexure. Peripheral basins form on the plate that is subducted during the collision of tectonic plates at a convergent boundary. Retroarc basins form on the overriding plate and can be found behind the magmatic arc.	Thermal gradients and heat flow are low, and the nature of fluid migration is in response to deformation. Porosity is often low due to sediment compaction. Relies on secondary porosity and permeability, which coupled with low gradients and heat flow would require long, slow flow paths for fluid heating.
			India		
			Pakistan		
		Northern Tarim Basin	Himalaya		
		Perian Gulf			
		North Alpine Basin	Austria		
			Switzerland		
			Germany		
			France		
		Ebro Basin	Spain		
		Western Canadian Sedimentary Basin	Canada		
	Foreland Basin (retroarc)	Southern Junggar Basin	Himalaya		
		Po Basin	Italy		
		Aquitaine Basin	France		
		Upper Magdalena Valley	Colombia		
		Cesar-Ranchería Basin			
		Llanos Basin			
		Middle Magdalena Valley			
		Caguán-Putumayo Basin			
		Eastern Venezuela Basin	Venezuela		
		Barinas Basin			
		Neuquén Basin	Argentina		
		Cuyo Basin			
		Oriente Basin	Ecuador		
		Magallanes Basin	Patagonia		

Appendix C - Opportunity Profiles

Business Growth

Economic Development

Technology Commercialisation

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