A PRE-FEASIBILITY STUDY FOR ENERGY RECOVERY FROM GEOTHERMAL PROSPECTS IN SCOTLAND

Paul Groves, Aaron Hochwimmer[1] and Jose (Jun) Seastres Jr.

[1]Sinclair Knight Merz Limited, PO Box 9806 Newmarket, Auckland, New Zealand

arhochwimmer@globalskm.com

Keywords: *Scotland, Engineered Geothermal System (EGS), Resource Assessment, Power Generation, Technology Demonstration, Skills Transfer*

ABSTRACT

An appraisal of geothermal prospects across Scotland has been undertaken by Sinclair Knight Merz (SKM). This appraisal has led to a concept study for the potential design, build and operation of a geothermal technology demonstration project in North East Scotland.

The assessment of prospects has indicated that the Cairngorm Granite Suite (Petrothermal/Engineered Geothermal System) and Midland Valley (Hydrothermal/Hot Sedimentary Aquifer) have the best potential for energy recovery. A stored heat assessment indicates recoverable reserves of 7,000 PJ_{th} and 4,800 PJ_{th} respectively. In the Cairngorm Granites, resource temperatures are estimated to be 135 °C at 5 km depth. In the Midland valley, temperatures are estimated to be 100 °C at 4 km depth. These prospects are considered as Inferred Resources due to the absence of offset well data to target depth. The temperatures are low compared to other geothermal project developments.

A project concept of two production wells, two injection wells and electricity generation from an Organic Rankine Cycle Plant was analysed, with well productivity based on analogous systems. This concept is estimated to produce 1.6 MW_e (gross), 740 kW_e (net) of electrical power. Financial analysis indicates a levelised cost of £875/MWh which is not economically feasible compared to alternative forms of renewable generation. A sensitivity analysis offered a comparison of how levelised costs may be impacted by a change in well configuration, temperature increase, or reduced capital costs.

SKM's technical and financial analysis of a conceptual geothermal project in Scotland suggests that at this stage such a project would rely heavily on government subsidies in order to become a commercial power generation plant. Given this, SKM recommends that the conceptual project is more suited to technology demonstration rather than 'fully commercial' project development. This would serve to demonstrate the transfer of knowledge and engineering skills that exist in Scotland.

1. INTRODUCTION

Sinclair Knight Merz (SKM) was engaged to provide Scottish Enterprise with a study into the geothermal opportunity for Scotland, including a high-level pre-feasibility study for the design, build and operation of a geothermal technology demonstration plant. The five key objectives of the work were as follows:

1) Analysis of the geothermal industry with an emphasis on the identification of skills transfer opportunities, from oil and gas to geothermal;
2) An appraisal of the geological resource in selected areas across Scotland, with a particular focus on North-East Scotland;
3) An estimation of energy capacity and energy utilisation across selected areas in Scotland;
4) A technical and financial appraisal of a prospective geothermal technology demonstration project;
5) Recommendations for further steps to define the Scottish geothermal resource.

For this work, certain parameters such as temperature and pressure were extrapolated from surface data or from shallow well measurements. Some relatively deep well data was made available from the Conoco well (2073 m) in the Firth of Forth and from the Weatherford Bridge of Don 3 well (1494 m) in Aberdeen. Permeability and well productivity was estimated by consideration of analogous projects and geological settings. The assessment presented in this paper is limited to information in the public domain along with the well data specifically noted.

2. GLOBAL GEOTHERMAL PERSPECTIVE

Geothermal energy has a special position amongst renewable energy sources due to its predictable base load capability. Thanks to its independence from climatic conditions, it can be used year-round, 24 hours a day with a relatively constant production price and a very high capacity factor (the best ratio of all energy technologies with up to 100 % availability). Deep geothermal energy is a clean, sustainable, reliable, highly efficient and viable energy source for direct heating, cooling and power supply. At present, around 10 GW_e of geothermal power are installed all over the world. On a global scale, development has been concentrated in a small number of countries with high enthalpy magmatic-type geothermal resources that can be economically exploited using well established technologies without the need for detailed and specific support frameworks. Over the last decade, new approaches both technical (i.e. advances in down hole pumping) and regulatory (i.e. favorable feed in tariffs) have helped make geothermal power generation economically viable across a wider area.

3. UK GEOTHERMAL PERSPECTIVE

In the UK, there are two geological settings which lend themselves to possible commercial geothermal development – Hot Sedimentary Aquifer type hydrothermal systems and Hot Dry Rock or Hot Fractured Rock type petrothermal systems. Throughout Europe there are already examples of geothermal developments of both of these types. High temperature resources are usually associated with volcanic heat sources and within Europe are generally only found near the surface in Iceland and South East Europe (i.e. Italy, Greece, and Turkey). There are no known high temperature volcanic-hosted resources in the UK.

The skills required in developing geothermal projects have very close similarities to the skills required to develop oil and gas projects. Scotland has a world-class oil and gas supply chain and SKM considers that the crossover potential from oil and gas into geothermal offers a strong opportunity in fulfilling the project aim to encourage the transition of skills, technology and knowledge into low carbon sources.

4. RESOURCE CHARACTERISATION OF SCOTLAND

The reservoir characteristics such as lithology, thermal profile, permeability and porosity of potential geothermal resources in Scotland were assessed based on research and data gathered from a range of publically available authoritative references. However, a major consideration in the resource assessment is proximity to the Energetica Corridor, i.e. an industrial region between Peterhead and Aberdeen (Figure 1, see attachment at rear). A map of identified geothermal opportunities is also provided in this figure. SKM's assessment of geothermal resources in Scotland indicates that the Cairngorm Granite Suite and Midland Valley have the best potential for energy recovery. They are located southwest of the Energetica Corridor.

The sandstone formation in Midland Valley, specifically in Fife, has good aquifer properties suitable for geothermal development assuming that the high porosity (>20 %) and permeability (>600 mD) based on shallow wells (<80 m) are similarly encountered at deeper levels. However, the estimated temperatures at depth are relatively low, i.e. a projected temperature of 100 °C at 4000 m.

There is some available downhole temperature data from the Midland Valley sector that is based on Conoco well 25/26-1, Firth of Forth 1. This well was drilled in 1990 to a depth of 2073 m true vertical depth. The well temperatures were measured during drilling and do not represent stable subsurface temperatures as this well was contaminated with drilling fluids during that time. Higher temperatures might have been expected if the well fully heated up and recovered from drilling fluid contamination. A typical well heat-up time period is normally in the region of 1 month. Nonetheless, the Conoco well 25/26-1 (Firth of Forth 1) had measured temperature at its upper part of more than 30 °C/km, even when considering that it was contaminated with drilling fluid. This suggests that a higher thermal gradient at stable temperature condition could be encountered particularly at greater depths.

The Cairngorm Granite Suite has a heat production rate of >6 μW/m^3 and a projected temperature of 135 °C (by modeling) at 5000 m (i.e. the maximum drilling depth technically and economically feasible based on field data from analogous projects). Recently, the surface heat flow is believed to be due to post-glacial warming at the end of the last glaciation that caused the melting of Quaternary ice cap in Scotland and significantly caused lower heat flow values particularly those measured from boreholes at shallow depths, i.e. <300 m in Scotland (Stephens, 2010; Busby, 2010; Younger *et al.*, 2011). The heat production outputs and heat flow values of granites of the Cairngorm suite generally do not differ much, although there are several areas that have higher heat production values relative to the others.

It must be noted that there is a large uncertainty in the temperature estimate as it is based on temperature modelling that considers the heat flow and thermal conductivity of rocks rather than measured temperatures at deeper levels. The inferred temperature of 135°C appears to be in the technically feasible range for binary power plant generation but at depths where drilling risks and economic costs are considerable.

Well temperature data is available within the Cairngorm Granite Suite but this is from wells located in the Bridge of Don, Aberdeen where the heat production values are relatively low (<4 μW/m^3) compared to other granites in this suite. The wells are situated within the Weatherford Evaluation Centre site where the deepest bore hole is 1494 m true vertical depth. A full suite of electric logs were run in the deepest well, Test Borehole 3. SKM reviewed the well logs (Figure 2) and the bottom hole temperatures at various depths. The temperature measured at the bottom hole is 32°C in which the thermal gradient is much lower than the 26°C/km average UK geothermal gradient (Busby, 2011) although this was measured during drilling and hence, it does not represent a stable well temperature after heat up recovery.

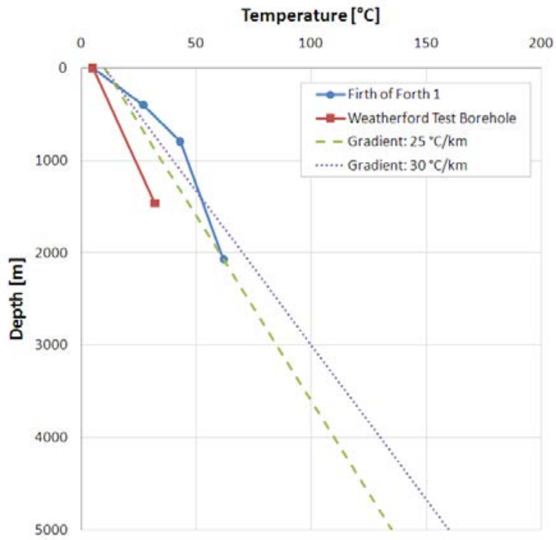

Figure 2: Offset well temperature profiles (the dashed and dotted lines reflect assumed thermal gradients and are provided for reference)

Other researchers (Busby (2010), Barker et. al (2000)) have estimated temperatures at 7 km depth through analysis of heat flow values combined with a generalized thermal conductivity/geological section. They concluded that, for the UK, temperatures could be as high as 260°C within the granites of southwestern England and 240°C within the buried granites of northern England, but temperatures rarely exceed 140°C elsewhere. Additional off-set data to at least 5 km depth would provide confidence on expected resource temperatures.

5. ESTIMATING ENERGY AT SURFACE

The energy capacity estimate is based on the stored heat assessment which determines the heat stored within the defined reservoir volume, above some rejection or base temperature and based on an assumed energy conversion technology with conversion efficiency less than 100%.

The stored heat includes both the heat stored in the rock and the heat stored in the reservoir fluid, though in almost all cases the heat stored in the rock will strongly dominate, even in high porosity naturally convective reservoirs.

The reservoir volume is usually taken as the area extent multiplied by the drilled depth plus some storage volume, commonly another 500 m in convective reservoirs, but a smaller figure should be used in conductive reservoirs, such as those described here, because of the slower rate of heat transfer. It is also very easy to include within the rock volume, regions of low permeability that in practice will not contribute to the producible reserves.

The Australian Geothermal Reporting Code (AGRCC, 2010) has been adopted in the stored heat assessment of Scotland geothermal prospects.

A summary of the stored heat and recoverable thermal energy of Scotland geothermal resources with potential for geothermal development are listed in Table 1. The stored heat results indicate that Cairngorm Granite suite has the highest recoverable thermal energy. The Fife area in Midland Valley has significant recoverable thermal energy, although this is more suitable for direct heat use due to relatively low temperature based on available well data (i.e. 100°C at 4000 m).

Table 1: Stored heat assessment results

Resource Area	Resource Type	Stored Heat [PJ_{th}]	Recoverable Thermal Energy [PJ_{th}]
Cairngorm Granite 1	Petrothermal	49,920	7,000
Cairngorm Granite 2	Petrothermal	46,650	6,500
Midland Valley, Fife Area	Hydrothermal	9,600	4,800
Cairngorm Granite 3	Petrothermal	7,820	1,100
Cairngorm Granite 4	Petrothermal	7,060	1,000

The above resources are all categorised as Inferred Resources which has the lowest level of confidence among the geothermal resource classification, due mainly to a lack of drilling and well testing. It is based on inferred estimate and has not been confirmed by actual well data to target depth.

The four granitic resources were identified for further analysis, and a system of two production wells and two injection wells was investigated using a hydraulic model of the wells and power plant.

It is possible that the suggested deep wells might not encounter water-saturated, permeable rocks. It is assumed that power generation would be from a Hot Dry Rock (HDR) or Enhanced Geothermal System (EGS) scheme. Injected water at the surface would be required.

The granite is considered to be enhanced through hydraulic fracturing and chemical stimulation at 5000 m depth and the resource temperature has been taken as 135 ºC. For the calculation of pumping loads the reservoir pressure at 5000 m is assumed to be warm hydrostatic with a water level to surface.

Three different scenarios were run, which reflect a range of expected well productivity indices that could be expected to be obtained based on reported experience in other EGS projects (e.g. the Soultz-sous-Forêts project as detailed in Genter et. al. (2008)). The three scenarios reflect well productivity/injectivity of 0.2, 0.5, and 0.8 l/s/bar respectively. The optimum flow rate was then obtained by maximizing the net power available from the system (refer Figure 3). At high flow rates the relatively high parasitic cost of brine pumping impacts the net power available. The key results are presented in Table 2.

Table 2: Energy utilisation estimates

Resource Area	EGS/1	EGS/2	EGS/3
Productivity Index [l/s/bar]	0.2	0.5	0.8
Optimum Flow per well [kg/s]	11.1	25.5	36.2
Total Flow [kg/s]	22.3	51.1	72.4
Gross Power [MW_e]	0.68	1.57	2.21
Net Power [MW_e]	0.32	0.74	1.09
Thermal Energy available from waste heat [MW_{th}]	4.6	10.7	15.1

Air cooling has been assumed for the plant heat rejection system and the power reported reflects the generation at an ambient dry bulb 'P50' temperature. There will be diurnal and seasonal fluctuations (the plant will produce more power in cold conditions and less power in hot conditions relative to the design point). The power plant is modeled as rejecting the brine at 70 ºC, which is a typical value for this technology. In addition waste heat from the brine is calculated by assumed a 50 ºC drop prior to injection back into the reservoir (i.e. 70 – 50 = 20 ºC).

EGS/Scenario 2 is the base case and indicates that at a flow-rate of 25.5 kg/s/well a power plant could produce about 1.57 MW_e (gross), which equates to about 740 kW_e (net) once plant and pump parasitic load has been accounted for. After about 49 kg/s the plant would not produce any net power. This is shown graphically in Figure 3. This is a very modest power output for the outlay of four wells and associated pumping and plant infrastructure. In order to benchmark this, a previous report (MIT 2006) established that for an EGS project to be commercially viable, it would need to have a production rate of 80 kg/s with a well head temperature of 200 °C. The current understanding of reservoir temperature of 135 °C at 5000 m depth is significantly below these criteria.

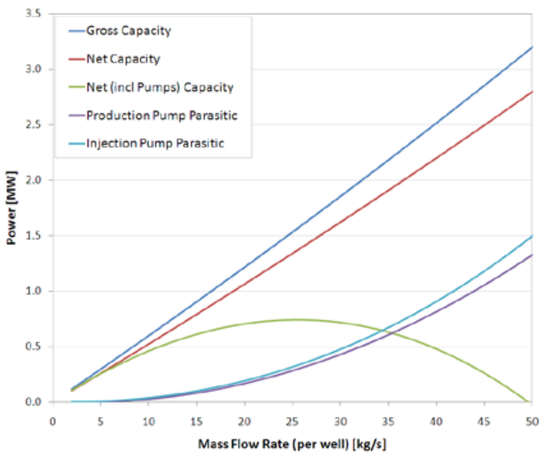

Figure 3: Power estimates (gross and net)

The results show that over half the gross power is “lost” due to the cost of extraction. This is a function of the relatively poor values of well productivity index (PI) that would be expected based on observations on analogous systems.

The twin doublet system (four wells) will produce relatively modest flow rates of fluid at 70 ºC (after it exits the power plant heat exchanger). The base case will produce about 10.7 MW_{th} in waste heat that could be utilised in a small scale (e.g. drying process, green house heating in winter). This assumes that a drop of 50 ºC (i.e. 70 ºC - 20 ºC) is achievable.

6. FINANCIAL ANALYSIS

In order to define a concept on which to develop the financial model for the geothermal technology demonstration project, SKM created a multi-criteria assessment of different project characteristics, including factors such as skills development and transfer opportunities, quality of the geothermal resource, economic criteria, and proximity to North East Scotland. Using this tool, and in consultation with project stakeholders, it was decided to select a project concept using a sub-block of the Cairngorm Granite Suite as the resource base, and to consider the use of EGS techniques for recovery of both heat and electricity from the petrothermal resource. The Cairngorm granite suite is shown in more detail in Figure 4 (refer to attachment at rear)

The well field to support the project was assumed to be a twin-doublet (that is two production wells and two injection wells). A binary plant is proven commercial technology and is the most appropriate readily available plant for this type of application. The design, construction and operation of the plant and associated resource development, drilling technology, and fluid gathering and disposal system provide an opportunity to develop Scottish skills to a wide range of geothermal power generation technology. The construction of fluid gathering system and associated equipment would give the greatest initial opportunity to apply existing skills.

As discussed previously, the project would be expected to generate between 0.3 MW_e and 1.1 MW_e net power. The range reflects the variability of well performance that could potentially be achieved through the stimulation process, which is undertaken to try and enhance well production performance. There is inherent uncertainty in the deep reservoir temperatures prior to drilling and this may further influence the power available.

For this study the 5 km deep wells were assumed to cost £10,000,000 each, based on a nominal rate of £2,000/m.

A scenario based approach was then used to perform the financial analysis and the base case (0.74 MW_e net) scenario resulted in a levelised cost of £875/MWh.

SKM have assessed the revenue projection of the plant and concluded that a range from £163-190/MWh will exist over the period to 2030, based on the current level of geothermal support from the UK government. This means that a funding gap (the difference between the cost of the project and the revenue accrued from the project) for the plant base case scenario will be between £685-712/MWh.

Furthermore, analysis of the project cost and revenue streams (NPV of revenues calculated over 25 year project life) allows for the identification of a project funding gap based on a present value price basis, such that all future cost and revenue streams are present valued back to a constant price base (assumed to be 2012) at a consistent discount factor (assumed to be 10%). The results of this analysis are presented in Table 3. The CAPEX and OPEX for the base case is £42.7M (NPV of CAPEX over 5 year construction period) and £6.8M (NPV of OPEX over 25 year project life) respectively. It is apparent from this analysis that the funding gap is lower for those project scenarios with higher reservoir temperature and/or a greater government support.

Table 3: Funding gap analysis

Scenario	Total Net Present Cost [£M]	Estimated Total Revenue [£M]	Funding Gap [£M]
Base case with 135 ºC reservoir, current government support	49.5	6.9	42.6
Base case with 135 ºC reservoir, increased government support	49.5	11.7	37.8
Base case with 165 ºC reservoir, current government support	49.5	22.2	27.3
Base case with 165 ºC reservoir, increased government support	49.5	38.0	11.5

7. SENSITIVITY ANALYSIS

In order to challenge the robustness of SKM’s cost analysis, a number of key performance parameters were subjected to sensitivity analysis, i.e.:

- Reduced Capital Cost (i.e. wells);
  - Up to a 30% reduction in drilling cost (i.e. from better than expected drilling times)
- Temperature Increase;
  - Up to 165°C, although it is noted that this is speculative at 5km depth in any area of Scotland.
- Well Configuration;
  - Reducing the number of wells through the trade-off of increased parasitic pumping power.

A summary chart of the sensitivity analysis is shown in Figure 5. It can be seen that reservoir temperature increase, along with well flow rate, are by far the most significant influencing factors in plant performance and the consequent financial performance.

Considering the sensitivity case of an increased reservoir temperature of 165 ˚C only (excluding reduced drilling costs), then the lifetime levelised cost was found to be around £270/MWh. SKM’s revenue projection concluded that a range from £245-268/MWh will exist over the period to 2030 if an increased level of government support was available for the geothermal technology demonstration project. An increase in reservoir temperature in combination with increased government support would make the project borderline commercial.

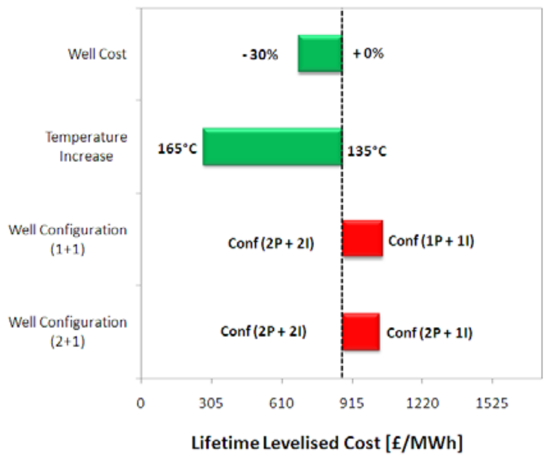

Figure 5: Graphical representation of key sensitivities

8. OPTIONS TO FURTHER DEFINE THE SCOTTISH RESOURCE

In the early phases of a geothermal project it is possible to significantly reduce project risk for a comparatively low cost in the overall project life cycle. SKM recommended that consideration be given to undertaking a geophysical survey programme which could help provide some confirmation of the conceptual model of the granitic bodies, in particular the depth and subsurface extent. Common techniques for this type of geological environment include seismic, gravity, and magnetic methods. These surveys would be of great assistance in defining potential drilling targets in the granite reservoir.

Furthermore, as part of this assignment, SKM visited the Weatherford Evaluation Centre in Aberdeen, where 4 wells have been drilled into granite formations. Further downhole temperature surveys would be useful to determine the stable well temperatures in the existing relatively deep wells as the temperatures measured in these boreholes may be misleading given that they were obtained at a time when the thermal condition was unstable due to drilling fluid contamination. A further investigatory option would be to approach WEC and assess the feasibility of drilling the wells deeper (c. 1000 m) into the prospective granite resources of the Cairngorm granite suite to obtain a reliable temperature data and evaluate the morphology of the granite in this sector.

SKM also highlighted the work of the Resonance Enhanced Drilling (RED) team at Aberdeen University, and suggest that this technology might be considered for use in the geothermal application. SKM has previously investigated the potential to implement RED into the geothermal industry, in particular granite-hosted EGS projects.

9. CONCLUSIONS

1) A conceptual geothermal technology project would rely on government subsidies in order to become a commercial project.
2) However, a technology project could serve to demonstrate the transfer of knowledge and engineering skills that exist in Scotland.
3) Surface geophysical surveys and/or shallow slimholes would help further define the geothermal resource.
4) Any skills transfer programme should be undertaken carefully in order to address the specific risks that are present in geothermal project developments.

ACKNOWLEDGEMENTS

We would like to thank Scottish Enterprise (SE) for permission to publish the findings of this study.

SE is Scotland's main economic development agency and aims to deliver a significant, lasting effect on the Scottish economy. SE's role is to help identify and exploit the best opportunities for economic growth. SE supports ambitious Scottish companies to compete within the global marketplace and help build Scotland's globally competitive sectors. SE also works with a range of partners in the public and private sectors to attract new investment to Scotland and to help create a world-class business environment.

We would like to acknowledge the input of Ken Mackenzie for his peer review of this paper.

REFERENCES

AGRCC: *The Geothermal Reporting Code: Australian Code for Reporting of Exploration Results, Geothermal Resources and Geothermal Reserves.* Prepared by the Australian Geothermal Reporting Code Committee (AGRCC), 2nd edition, (2010)

Barker, J.A., Downing, R.A., Gray, D.A., Findley, J., Kellaway, G.A., Parker, R.H. and Rollin, K.E. *Hydrogeothermal studies in the United Kingdom.* Quarterly Journal of Engineering Geology and Hydrogeology, 33. 41-58 (2000)

Busby, J.: Geothermal Prospects in the United Kingdom *Proceedings of the World Geothermal Congress,* (2010)

Busby, J,: UK Data for Geothermal Resource Assessments. *UK First Geothermal Symposium,* (2011)

Genter, A., Fritsch, D., and Cuenot, N. *The Soultz EGS power plant: from the concept to power production,* IGA News No 71 (2008)

Massachusetts Institute of Technology (MIT): The Future of Geothermal Energy – Impact of Enhanced Geothermal Systems (EGS) in the United States in the 21st Century. *MIT/US Department of Energy,* (2006)

Stephens, E.: *Geothermal Energy in Scotland: Exploring the Territory and Identifying Opportunities* (2010)

Younger, P. L., Stephens, W.E., and Gluyas, J.G.: Development of Deep Geothermal Energy Resources in the UK. *ICE Proceedings - Energy,* Volume 164, ENO (2011)

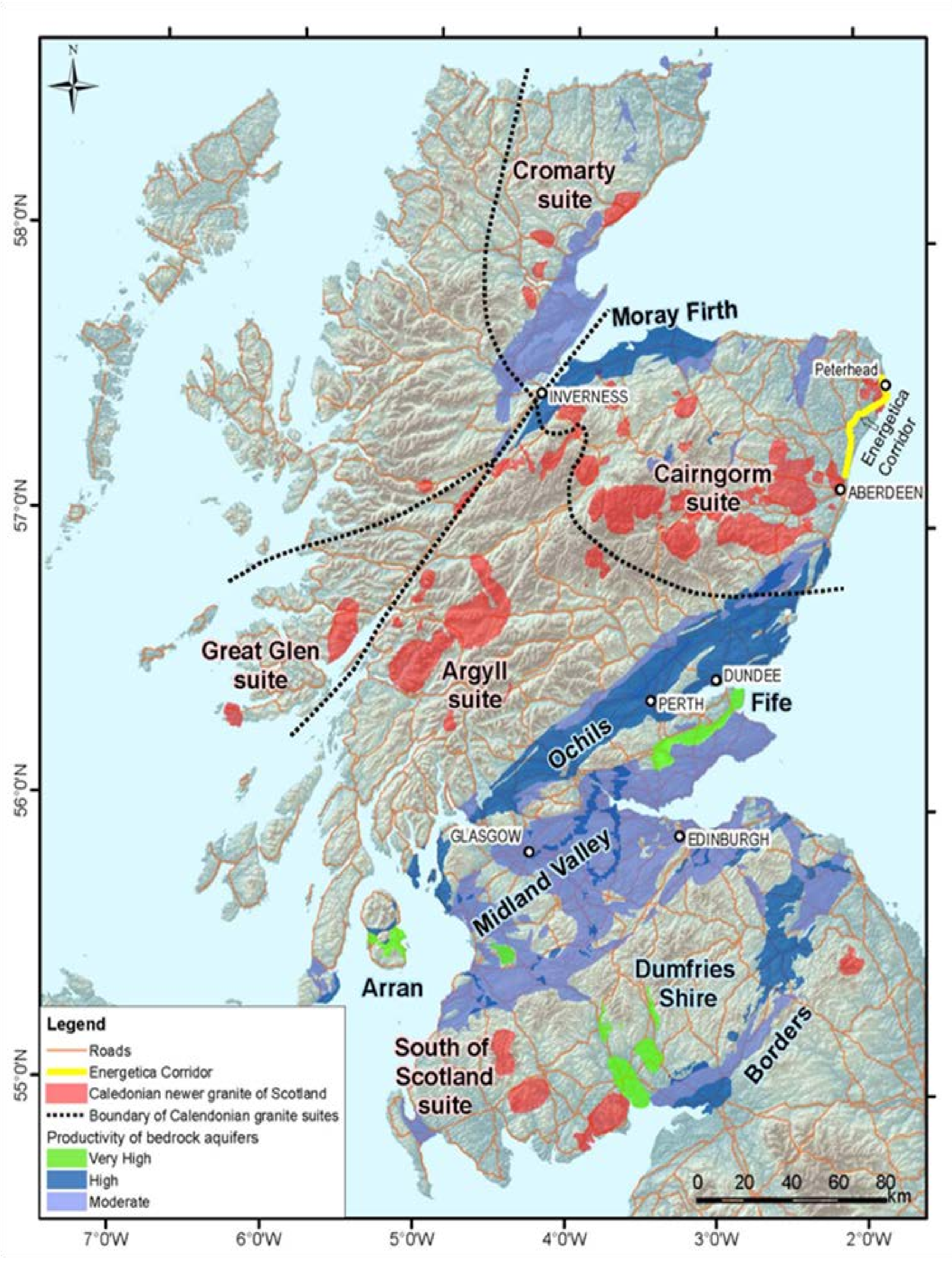

Figure 1: Scottish geothermal resources, modified from Younger *et. al*. (2011)

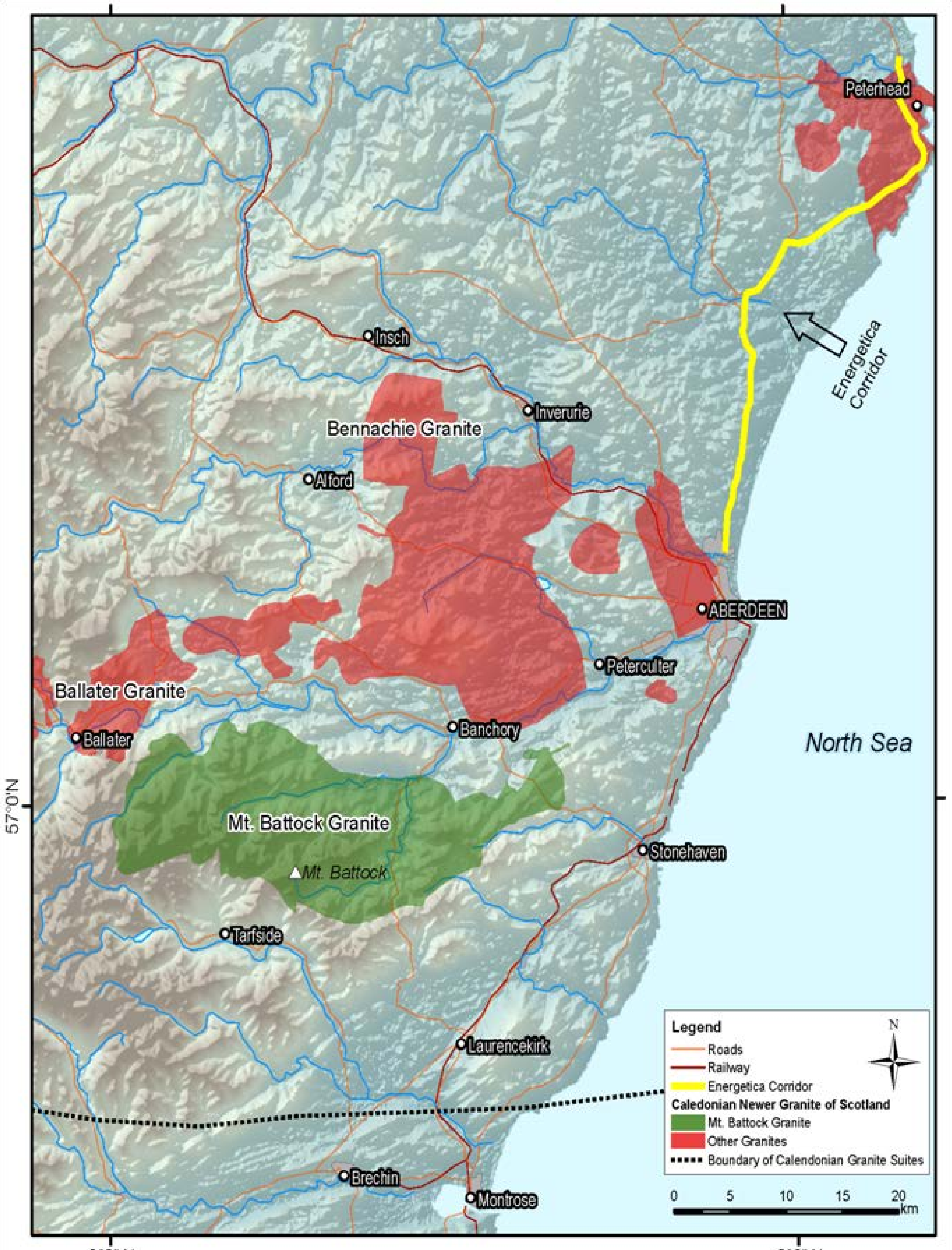

Figure 4: Cairngorm granite suite