British Geological Survey

The geothermal resource of the radiothermal granites of the UK

Summary

- Engineered geothermal systems (EGS), also termed 'hot dry rock' or 'petrothermal' systems, make use of crystalline basement rocks such as granite. Granites have enhanced heat flows due to enrichment of the radioactive elements uranium, thorium and potassium, making them particularly suitable as a geothermal resource.
- To be most suitable for EGS, granites must be extensive in size and have high heat flows, and often have natural permeability in the form of fault zones.
- In the UK, four areas satisfy these criteria: south-west England, northern England, the Scottish Highlands and the Mourne Mountains of Northern Ireland. The areas with the currently identified best potential lie in the south-west and north of England.
- To date, the only exploited resource for heat and power is found in the south-west of England.

Background

The geothermal potential of the UK was first investigated in the 1970s and a major review of geothermal resources was subsequently undertaken (Downing and Gray, 1986). While the UK lacks the geological and tectonic setting requirements for high-temperature geothermal exploitation, low- to moderate-temperature sources provide heat and, in some cases, electricity. The resource with the highest potential for medium-enthalpy (total heat energy) geothermal was identified as 'hot dry rock' radiothermal granites. The 'hot dry rock programme' (from 1977 to 1994) explored the geothermal potential of granites within the UK and included experimentation on the granites of Cornwall (for example, Rollin, 1982; Parker, 1999).

Target temperatures for engineered geothermal systems (EGS) depend on the use of the heat. Temperatures in excess of 150°C are currently required for economic electricity production. Lower temperatures may be used for direct heating.

Research studies since the 1980s have examined:

- the resource base for EGS in Britain (Busby and Terrington, 2017)
- the geothermal potential of Scottish granites (for example, Gillespie et al., 2013; Busby et al., 2015: McCay and Younger, 2017)
- corrections to the geothermal dataset accounting for palaeoclimate and topography (Westaway and Younger, 2013)

- estimates of heat production and flow from the Cornubian batholith (Beamish and Busby, 2016)
- the geothermal potential of the north of England (Brown, 2022)

An exploration well was drilled at Eastgate in 2004, which was designed to intercept fracture-hosted brines associated with hydrothermal vein systems (Manning et al., 2007). Operational EGS heat and power projects have been developed in Cornwall since 2018.

The resource

In order to be suitable for geothermal exploitation, a body of crystalline rock must be extensive and have a suitable temperature. In the UK, this equates to a vertical and horizontal extent of 6 km (Lee, 1978) and temperatures of 175°C (Busby and Terrington 2017). Major granite plutons are the potential targets for EGS use, where regional heat flow is enhanced by high concentrations of heat-producing radioactive uranium, thorium and potassium. The plutons have large negative gravity anomalies. High background heat flow and low conductivity sedimentary cover are also important.

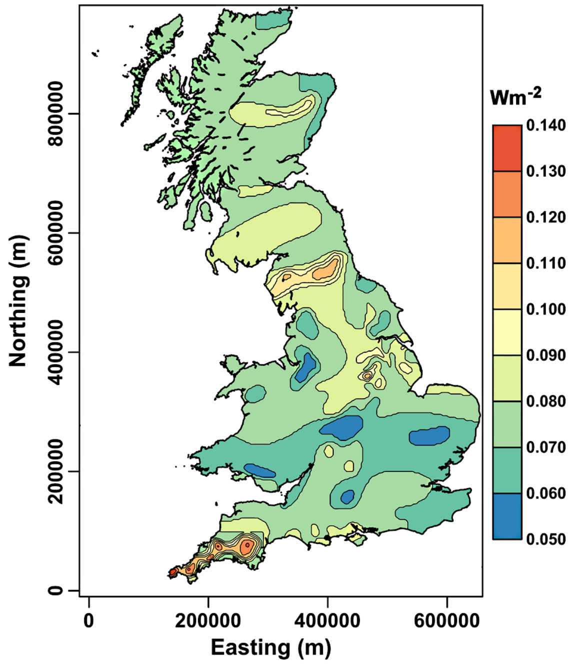

Figure 2 Map of surface heat flow in the UK (From Busby and Terrington, 2017, under http://creativecommons.org/licenses/by/4.0/).

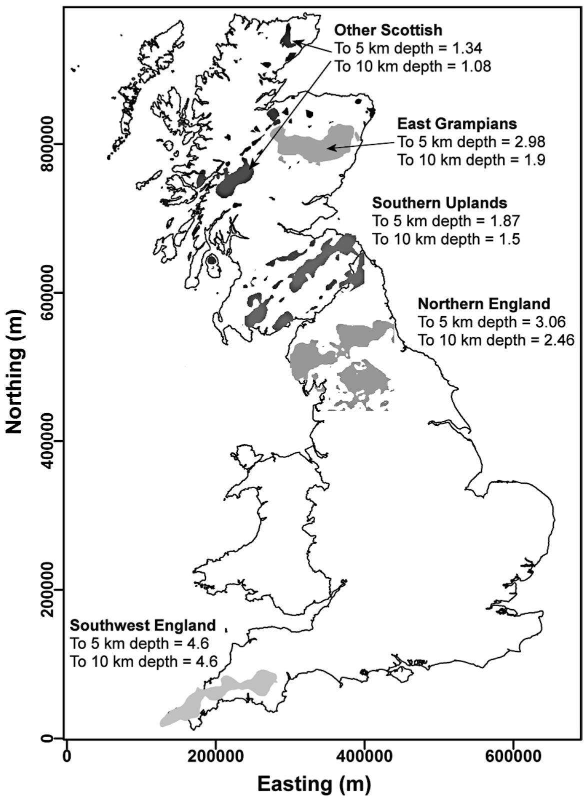

Figure 1 Map of known significant quantities of heat producing granites. Quantitative values for average heat production (µW m^3) shown for 5 and 10 km depths. (From Busby and Terrington, 2017, under http://creativecommons.org/licenses/by/4.0/). Note that the concealed Market Weighton and Wash granites are not shown.

Four areas of the UK satisfy these criteria (Downing and Gray, 1986):

- south-west England
- northern England
- the eastern Highlands of Scotland
- the Mourne Mountains of Northern Ireland

Granites of Ordovician to Devonian age are found in the Lake District and the north Pennines in northern England (including the Wensleydale and Weardale granites) and the eastern Highland granites of Scotland (BGS, 1984) and are thought to be related to the 'Caledonian' tectonic event. 'Variscan' granites of late Carboniferous to Permian age are found only in the south-west of England, forming the Cornubian batholith (Lee, 1978). Both post-Caledonian and Variscan granites are associated with large negative Bouguer gravity anomalies. Palaeogene-aged granites are found in Northern Ireland in the Mourne Mountains complex (Ture et al., 2016).

There are other non-Variscan and non-Caledonian granites around the UK. For example, there are Neoproterozoic-aged granites in North Wales and around the northern Highlands and Grampian terranes, and Neoarchaean-aged metamorphosed granites in the granitoid basement of the Hebridean terrane. These are not high heat producing and therefore not geothermal targets.

Regional geothermal prospects

Caledonian granites

The Caledonian granites of northern England and Scotland are divided into Devonian granites that are uranium enriched and pre-Devonian granites that have no significant uranium enrichment (Lee, 1978).

Lake District and north Pennines

The Lake District batholith covers an area of 1500 km^2 (Downing and Gray, 1986) and has a depth of 7 to 10 km (Lee, 1978). It connects the Eskdale, Shap and Skiddaw granites, with Shap and Skiddaw having the highest heat flows. However, these are small in surface area and marginal to the main Lake District batholith. Temperature estimates in the Shap and Skiddaw granites at 2 km depth are 57°C and 63°C, respectively, and 148°C and 160°C, respectively, at 6 km (Downing and Gray, 1986).

The Eskdale granite forms the central part of the batholith. Either weathering or oxidation by hydrothermal fluids could have released much of the original uranium, therefore the surface heat production estimate of 1.9 μW m^3 for the Eskdale granite is likely an underestimate (Downing and Gray, 1986). The average heat production for the area is 4.75 μW m^3 (Lee, 1978).

The Weardale granite covers an area of 1500 km^2 and, based on geophysical, gravity and magnetic anomaly modelling, is interpreted to reach a depth of 9 km to its base (Downing and Gray, 1986). The Rookhope borehole proved 390 m of Carboniferous sedimentary cover (Lee, 1978) and 417 m of granite. The sedimentary cover raises temperatures by 7°C compared to the same granitic rocks at outcrop by acting as a 'thermal blanket'.

At Weardale, the above-average uranium, thorium and potassium concentrations (Lee, 1978) lead to a heat flow of 115 mW m^{-2} and a heat production of 4.1 μW m^3, and the thermal conductivity of 2.99 W mK gives a geothermal gradient of 38°C km^{-1} as measured at the Eastgate borehole, drilled specifically for geothermal exploration (Manning et al., 2007). Therefore, temperatures of 150°C and 200°C are estimated at 4.4 km and 6 km, respectively. A temperature of 200°C may be found at 5 km where there is a greater thickness of sedimentary cover (Lee, 1978).

The heat-flow values from Shap, Skiddaw and Weardale confirm the Lake District–Weardale line of granites forms a large heat-flow zone (Downing and Gray, 1986). The greatest potential in this area is from the Weardale granite. The Shap and Skiddaw granites have also above-average potential, but 150°C is not estimated to be reached before 5.5 km depth. The Wensleydale granites, found to the south, are less radiothermal, with an observed heat flow of 65 mW m^{-2} (Downing and Gray, 1986) and a heat production of 2.9 μW m^3 (Lee, 1978).

The heat-in-place for the Lake District and north Pennine granites is estimated at 2639.9 exajoules (EJ) and the recoverable heat is estimated at 52.8 EJ (Brown, 2022). For electricity production only, the heat-in-place is 1856.1 EJ and recoverable heat is 37.1 EJ (Brown, 2022).

Scotland

Despite the granites of the eastern Highlands of Scotland having high heat production values (1.20 to 8.22 μW m^3 (McCay and Younger, 2017)), the surface heat flow is relatively low. This has been attributed to the effects of the palaeoclimate and glaciation on the shallow section of the geothermal gradient (Westaway and Younger 2013; Gillespie et al, 2013; McCay and Younger, 2017). After correction for palaeoclimatic effects and topographical influences, the granites represent better resources than previously assumed (McCay and Younger, 2017).

Four of the granites (Ballater, Bennachie, Cairngorm and Mount Battock) have high heat-production values (over 5 μW m^3). They are all part of the Cairngorm suite of granites and would be suitable for direct heating purposes. Five — Ben Rhinnes, Cheviot, Hill of Fare, Lochnagar and Mondadhliath — have marginal values (3 to 5 μW m^3 and may be suitable for direct heating purposes if the heating demand were to be in close proximity to the granite (McCay and Younger, 2017).

The corrected heat flows from the Cairngorm batholith have been measured between 58.7 and 86.0 mW m^{-2} (Downing and Gray, 1986; Busby et al., 2015) with a heat production of 5.12 to 6.45 μW m³ (McCay and Younger, 2017). Temperatures at 5 and 7 km within the Cairngorm batholith are estimated to be 129 and 176°C, respectively (Busby et al. 2015).

The Fearn, Abriachan and Helmsdale granites all have heat production values of over 4 μ/W m¹; however, Fearn and Abriachan are small and therefore of lesser significance for EGS. The Helmsdale granite is enriched with uranium due to secondary processes. Parts of the zoned Etive, Strontian and Ballachulish granites also have similar heat production values but only the Etive granite is associated with a large negative Bouguer gravity anomaly, which may indicate a large, radioactive-element-rich granite underlying the Etive intrusion (Downing and Gray, 1986.)

The mean heat production values for the granites of the Southern Uplands are generally not high (1.2 to 8.2 μW m³) (McCay and Younger, 2017). The Fleet, Loch Doon and Criffel granites are characterised by large negative gravity anomalies, suggesting the presence of large volumes of evolved granite at depth, and they appear to extend to depths of 10 to 12 km. They may therefore be similar in nature to the Lake District and Weardale granites (Downing and Gray, 1986). However, the relatively small surface area of the Criffel granite makes it a less attractive target (McCay and Younger, 2017).

Lowland Britain

Caledonian granites have been suggested at Market Weighton, where bottom-hole temperatures at South Cliffe indicate a geothermal gradient of 45°C km⁻¹ would give an uncorrected heat flow in excess of 100 mW m⁻² (Rollin, 1982).

Variscan

The only Variscan granites in the UK are found in Cornwall and the Isles of Scilly, in the form of the Cornubian batholith. This batholith is a proven successful target for EGS.

Cornubian batholith

The Variscan granites have similar uranium enrichment to the post-Caledonian granites (Lee, 1978). The Cornubian batholith comprises five granite bodies in south-west England and the Isles of Scilly at a depth of 10 to 20 km, interpreted from gravity anomalies. Heat flow is generally over 100 mW m⁻² at all outcrops, with a uniform heat production of 4.0 to 5.3 μW m³ (Downing and Gray, 1986; Barker et al., 2000; Beamish and Busby, 2016). Modelling

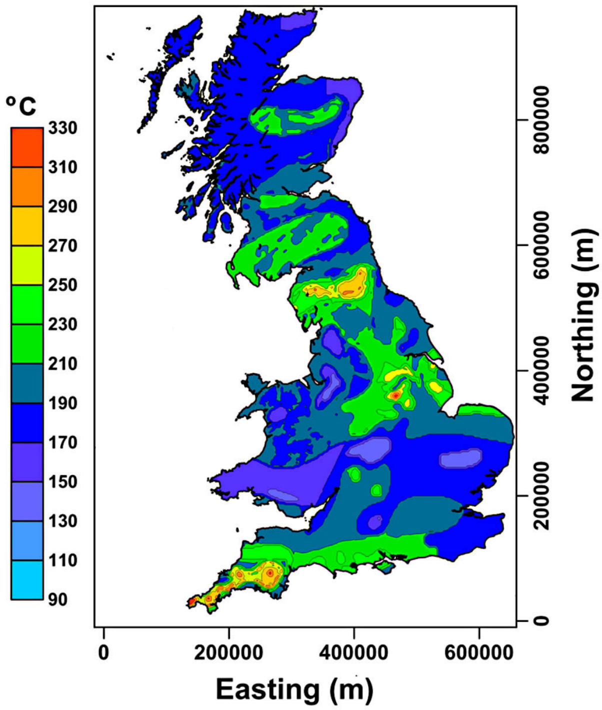

Figure 3 Temperatures at 7 km depth. (From Busby and Terrington, 2017 under http://creativecommons.org/licenses/by/4.0).

suggests temperatures at 7 km depth are likely to be between 210 and 330°C across the area (Busby and Terrington, 2017), which is consistent with shallower borehole measurements from the Carnmenellis granite (Downing and Gray, 1986). Temperatures measured at 5 km depth at Redruth are 180°C (Olver and Law, 2025). The heat-in-place for the Cornubian batholith is estimated at 8988 EJ (Turan et al., 2024).

Palaeogene

Palaeogene granites are found in the Mourne Mountains complex of Northern Ireland and are divided into the Eastern Magmatic Centre and Western Magmatic Centre.

Mourne Mountains, Northern Ireland

The Eastern Magmatic Centre is a granitic body that extends to depths of 5 to 6 km, while the Western Magmatic Centre extends to 4 to 5 km depth (Ture et al., 2016). The area has a heat flow of 84 to 87 mW m⁻², measured in two boreholes (Wheildon et al., 1985). The Eastern Magmatic Centre has a heat production of 7.79 μW m³, while the Western Magmatic Centre has a value of 6.56 μW m³ (Yarr, 2013). The geothermal gradient for the area is 21.07°C, measured from boreholes (Ture et al., 2016).

The high heat-production values suggest this area could be favourable for EGS; however, the modest heat flow and geothermal gradient mean the area requires further investigation before it can be claimed as suitable (Ture et al., 2016).

UK estimates

The total heat-in-place to a depth of 9.5 km in basement rock available for EGS is 357 197 EJ (Busby and Terrington, 2017). The total technical potential power to a depth of 6.5 km is 222 393 MW_e (Busby and Terrington 2017).

Operational projects

At present, the Cornubian batholith is the only radiothermal granite in the UK being exploited for geothermal energy. The United Downs deep geothermal power project, near Redruth in Cornwall, is the first deep geothermal power plant in the UK. The power plant uses a binary cycle ORC (Olver, 2025) and consists of two directional wells: a production well, drilled to a total measured depth of 5.275 km, and an injection well at 2.939 km (true vertical depths of 5.057 km and 2.214 km, respectively). The site is planned to deliver 3 MWe of electricity to the National Grid (Gordon, 2023.) The plant makes use of, and has enhanced the natural permeability, from a faulted 'cross-course' zone within the Carnmenellis granite (Farndale and Law, 2023). The area has a surface heat flow of 120 mW m^{-2} (GEL, 2025) and the geothermal gradient for the area is 33 to 35°C km^{-1}, which results in a bottom-hole temperature of over180°C (Olver, 2025).

GEL Energy has also developed the site for 'zero-carbon' lithium extraction using geothermal brines, which show high concentrations of lithium (over 300 ppm) (Menteth, 2023; Olver and Law, 2025). Cornish Lithium, Northern Lithium and Weardale Lithium and others are also looking to extract lithium from geothermal brines.

The single 4.871 km (5.277 km deviated length) geothermal borehole at the Eden Project is drilled into the St Austell granite of the Cornubian batholith and is used to heat the site's 'biomes' and a plant-nursery building. The coaxial system supplies heat at 85°C (Eden Project, 2025) via a heat exchanger. The borehole was drilled vertically to 1.7 km then directionally to intersect the Great Crosscourse Fault. It supplies heat via a 3.8 km long surface heat main (Eden Geothermal, 2025).

A research project is underway at the University of Aberdeen that will see a 500 m borehole, seismic survey and 3D imaging used to assess the geothermal potential of the Aberdeen granite for a district heating network (University of Aberdeen, 2025).

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