GEOTHERMAL ENERGY OPPORTUNITIES OF THE U.K.

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Abstract
The United Kingdom has significant and almost entirely unexploited geothermal potential. Heat won from hot sedimentary aquifers and naturally fractured granites and other ancient rock could be produced and used for district heating schemes. Geothermal heat is ultra-low carbon and secure energy.

The geothermal potential of individual council areas in the UK is here assessed and ranked. We demonstrate that many of the more populated areas of the UK also have high geothermal potential.

Introduction
The aim of this study was to identify and rank the geothermal potential of all parts of the United Kingdom. The work was commissioned by and delivered to the Rt Hon Kieran Mullan, Member of Parliament for Crewe and Nantwich.

Assessments of the geothermal potential of the UK have been undertaken on several occasions by the British Geological Survey and most recently by BritGeothermal (Gluyas *et al* 2018) a research partnership composed of the British Geological Survey along with the universities of Durham, Glasgow and Newcastle. Gluyas et al (*op cit*) estimated the minimum resource to be about 300 EJ_{TH}. This compares with an annual heating 'bill' for the UK of about 3 EJ_{TH}. That is to say, the resource to use ratio would enable supply to last for 100 years. The estimate was based only on hot water extraction and took no account of returning the cooled water into the subsurface for reheating. Moreover, no attempt was made to match the estimated resource with anticipated demand on any scale smaller than the whole nation. In this study we have used local councils (England 333, Scotland 32, Wales 22, Northern Ireland 11) to discritise the geothermal potential.

UK Geothermal Gradients
The temperature beneath the ground surface increases with depth. The rate of change of temperature with depth is known as the geothermal gradient and in the UK the average geothermal gradient is 28 °C km^{-1} (Howell *et al* 2021) and a maximum of about 38 °C km^{-1} (Younger *et al* 2016). Figure 1 shows an interpolation of measured temperatures 1 km beneath the surface. Many measurements are available for areas of petroleum exploration and production such as the East Midland, the Wessex, Hampshire, and Weald Basins. There are few deep temperature measurements elsewhere and none in northern Scotland and much of Wales.

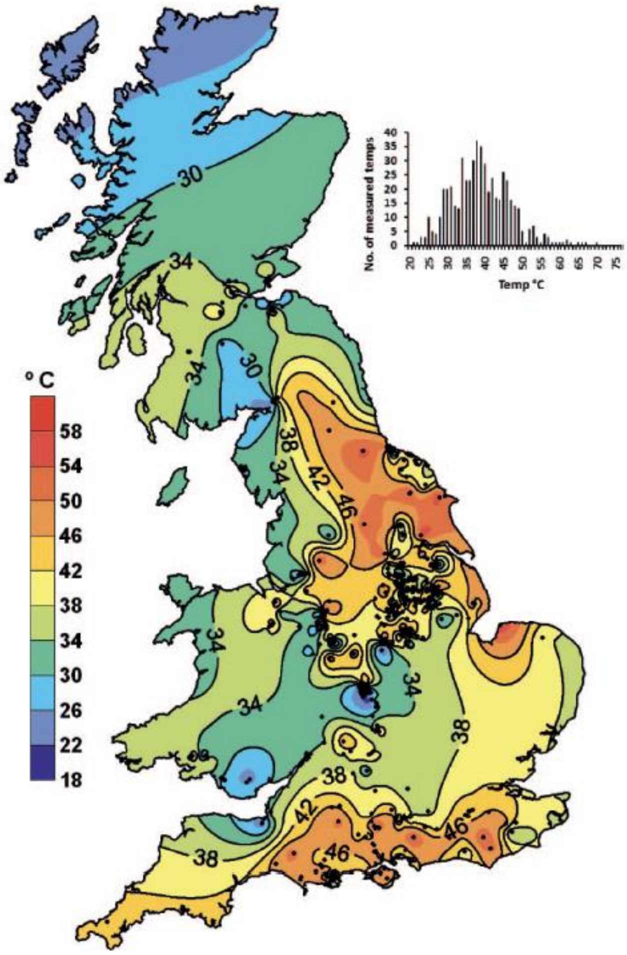


Figure 1 Measured temperature at 1 km below ground level. Black dots are measurement locations (from Busby et al 2011, Northern Ireland was not included in this study).

UK Aquifers & Granites

The geology of the UK displays a broad pattern in which the rocks found in NW Scotland are the oldest (more than 2 billion years old) and those found in SE England and East Anglia are the youngest (a few million years old). Typically, the younger sedimentary rocks are more porous (able to hold fluids) and permeable (able to transmit fluids) than the older rocks, although in some instances naturally fractured (old or young) rock, even that with low porosity, can have high permeability.

The British Geological Survey lists 11 principal aquifers in the UK. Where such aquifers are shallow, for example less than 500m, they are typically filled with fresh, potable, meteoric water whilst at depth they tend to be brackish or saline and contain connate water or a connate water/meteoric water mix. At depth, the water is warm to hot. Each is described below. Accompanying maps are from the BGS website, https://www2.bgs.ac.uk/groundwater/shaleGas/aquifersAndShales/maps/aquifers/home.html.

Crag – friable to consolidated sandstone of Pliocene to Pleistocene age, present only in easternmost East Anglia and at depth shallower than about -60 mOD. Not used in this study.

Chalk – microporous and jointed limestone of Upper Cretaceous age. The Chalk is a major aquifer of SE England and present in the subsurface as deep as -1000 mOD. The Chalk is the UK's most important aquifer for potable water (Lee *et al* 2006).

Lower Greensand – glauconitic sandstones with clay seams and of Lower Cretaceous age. It lies beneath the Chalk and has much the same distribution and depth range. It is an important aquifer in SE England and East Anglia (Edmunds *et al* 2007).

Spilsby Sandstone – sandstone of Lower Cretaceous age known only from eastern Lincolnshire and at depths of up to -200 mOD. Not used in this study.

Corallian Limestone – limestone with some interbedded gritstone of Upper Jurassic aga present near surface in Yorkshire and at depths of up to -1500 mOD in the Wessex Basin.

Oolites – a mix of limestones, sandstones, and clays of Middle Jurassic age present in the subsurface from the Wash in eastern England to the south coast where they are at their deepest at up to -2000 mOD.

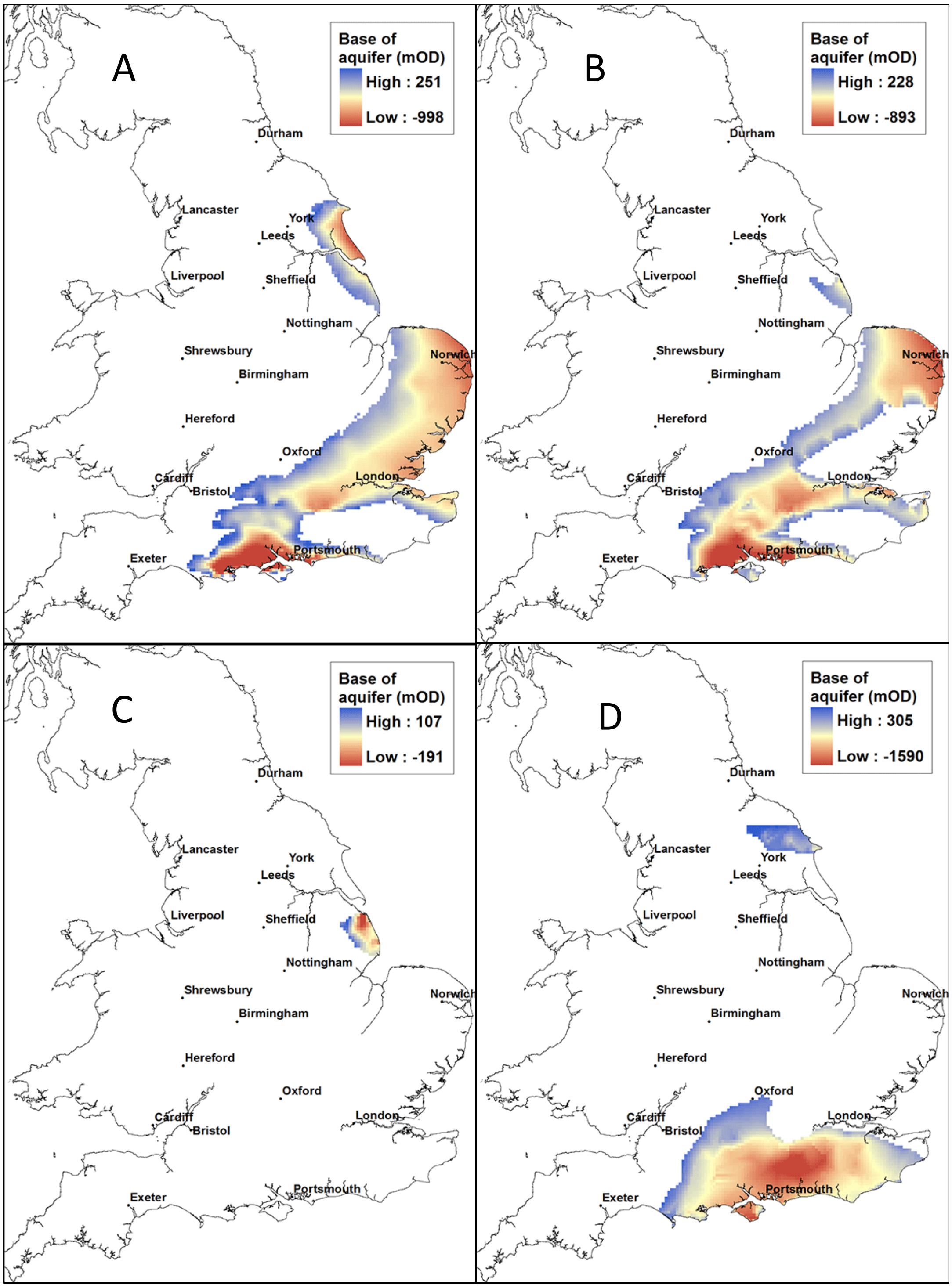
Triassic Sandstone – medium grained fluvial and aeolian sandstones of Triassic age that occur in a Y-shaped outcrop and subcrop flanking the Pennines in the north of England and with the stem of the Y stretching from the Midlands to the South Coast. The sandstones are present at depths to greater than -3500 mOD in the Cheshire Basin, Worcester Graben, and Wessex Basin. Extraction of geothermal water has been occurring from this horizon in Southampton since 1986 (Gearty *et al* 2008) and in Scunthorpe, North Lincolnshire since 2021 (Verney, 2021).

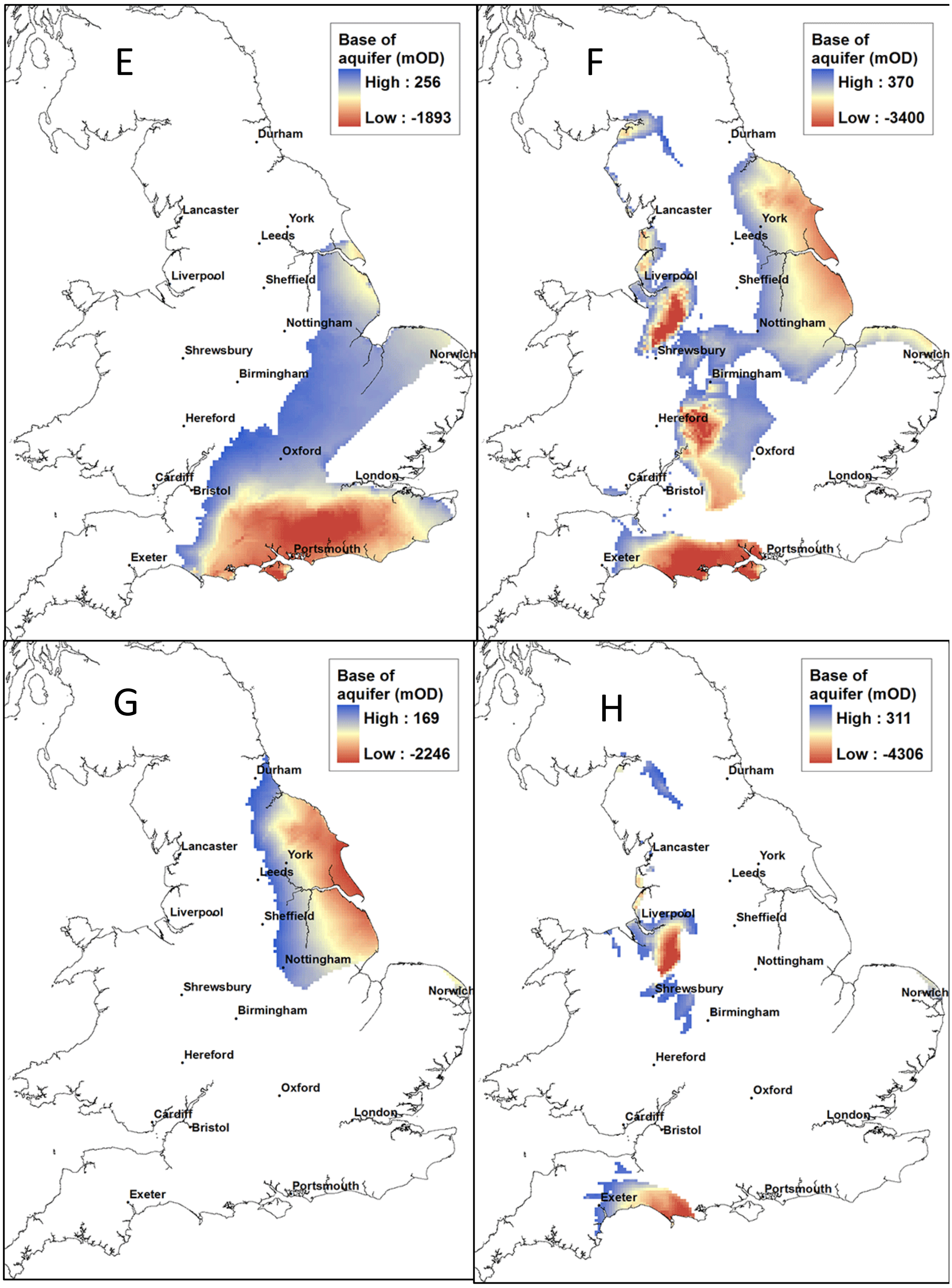
Magnesian (Zechstein) Limestone – crystalline and vuggy dolstones and limestones of Upper Permian age occur as an aquifer in east England from Lincolnshire to County Durham and at depth up to -2.3 kmOD (Daniels et al 2022).

Permian Sandstone – largely fine to medium granted aeolian sandstones of Lower Permian age which lie directly beneath the Magnesian Limestone in eastern England and at the core of the Cheshire and western parts of the Wessex basin at depths exceeding -4 kmOD.

Carboniferous Limestone – fractured and jointed, vuggy, and variably karstified limestones and subordinate dolstones of Lower Carboniferous age are widely distributed in the UK. These limestones are projected to occur at depth of more than -4.5 kmOD in the north of England, the East Midlands, parts of the Cheshire Basin, South Wales and Southern England (Narayan *et al* 2021).

Fell Sandstone and Border Group – fine to medium grained and jointed/fractures sandstones of Lower Carboniferous age occur in Northumberland and Cumbria (Sutton, 2022).


A
Base of aquifer (mOD)
High : 251
Low : -998
B
Base of aquifer (mOD)
High : 228
Low : -893
C
Base of aquifer (mOD)
High : 107
Low : -191
D
Base of aquifer (mOD)
High : 305
Low : -1590
Durham
Lancaster
York
Leeds
Liverpool
Sheffield
Nottingham
Shrewsbury
Birmingham
Norwich
Hereford
Oxford
Cardiff
Bristol
London
Exeter
Portsmouth


E
Base of aquifer (mOD)
High : 256
Low : -1893
Durham
Lancaster
York
Leeds
Liverpool
Sheffield
Nottingham
Shrewsbury
Norwich
Birmingham
Hereford
Oxford
Cardiff
London
Bristol
Exeter
Portsmouth
F
Base of aquifer (mOD)
High : 370
Low : -3400
Durham
Lancaster
York
Leeds
Liverpool
Sheffield
Nottingham
Shrewsbury
Norwich
Birmingham
Hereford
Oxford
Cardiff
London
Bristol
Exeter
Portsmouth
G
Base of aquifer (mOD)
High : 169
Low : -2246
Durham
Lancaster
York
Leeds
Liverpool
Sheffield
Nottingham
Shrewsbury
Norwich
Birmingham
Hereford
Oxford
Cardiff
London
Bristol
Exeter
Portsmouth
H
Base of aquifer (mOD)
High : 311
Low : -4306
Durham
Lancaster
York
Leeds
Liverpool
Sheffield
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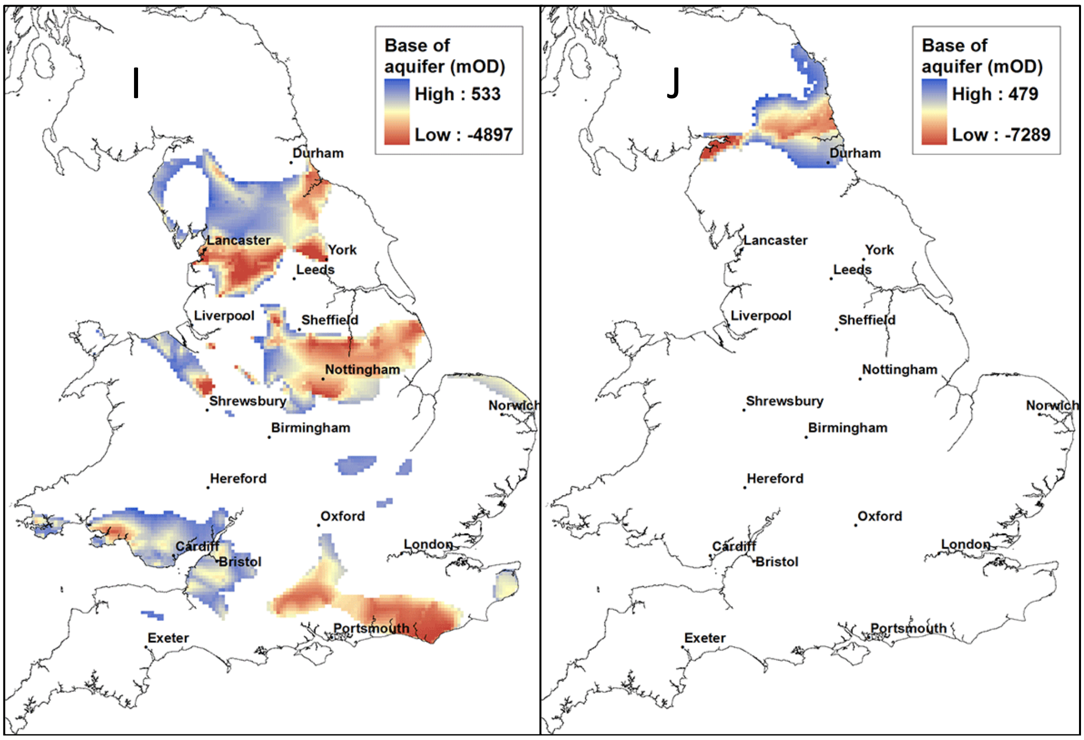

Figure 2 Outcrop and subcrop of key aquifers; A Chalk, B Greensand, C Spilsby Sandstone, D Corallian Limestone, E Oolites, F Triassic Sandstone, G Magnesian Limestone, H Permian Sandstone, I Carboniferous Limestone, J Fell Sandstone and Border Group (from https://www2.bgs.ac.uk/groundwater/shaleGas/aquifersAndShales/maps/aquifers/home.html.*).*

Temperature data

Temperature data used in this study are primarily sourced from the BGS Geothermal Catalogue (Rollin, 1987). These data were originally gathered from petroleum borehole data, mining records, and a number of boreholes drilled as part of geothermal studies in the BGS in the late 70's and early 80's. The Geothermal Catalogue was recently digitised and updated as part of a review of legacy subsurface data for nascent geoenergy activities onshore UK (Ireland *et al.,* 2021), this work was in part funded by the North East Local Enterprise Partnership. As a result, around 1700 temperature measurements taken across 942 sites are made available for use in this study. Over 85% of these measurements are from depths shallower than 1500 m, reflecting a scarcity of temperature data at depths typically associated with geothermal energy developments. Moreover, about 27% of the 1700 measurements are from depths shallower than 500 m. Considering parts of the near-surface temperature field have been perturbed by glaciation effects of the Quaternary (Westaway and Younger, 2013), geothermal gradients estimated from these shallow measurements alone may result in an underestimation of temperature at greater depths. Temperature corrections for borehole circulation effects have been published in the Geothermal Catalogue alongside their respective original measurements at various locations. These corrections are not included in this study, however, so that geothermal gradients can be derived consistently. While no temperature measurements recorded after 1987 are included in the Geothermal Catalogue, some have been added to the current dataset. The number of temperature data points in each area are shown by Figure 3.

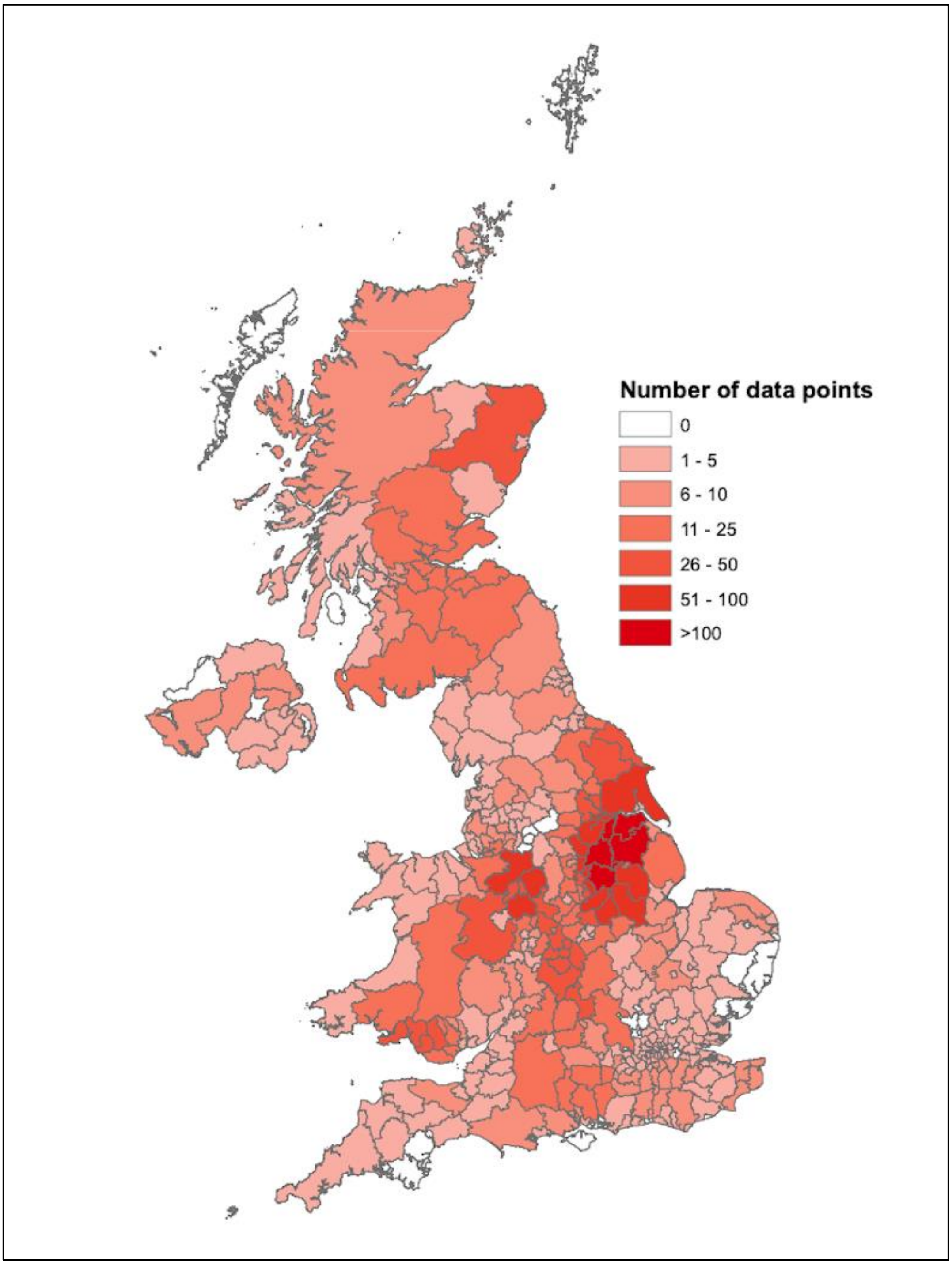

Figure 3 Temperature data abundance per council area.

Methodology - Hot sedimentary aquifers

Temperature and aquifer data were used in conjunction to assess the geothermal water and its potential supply in each council area at two depths, 2 km and 4 km. To do so, the average geothermal gradient for each council area was first estimated.

As previously mentioned, temperature data are available at 942 locations across the UK. Each location, hereinafter referred to as a data point, consists of one or more temperature measurements. Put another way, where a data point is an oil well, for example, multiple temperature measurements may have been recorded at varying depths in that well. In this instance, a geothermal gradient value is derived from each temperature measurement in the well in relation to the surface temperature, following equation 1. The average of each of these geothermal gradient values is the estimated geothermal gradient for that well. Surface temperature is conservatively assumed as 11°C for all data points. This assumption was made since surface temperature is unavailable in the digitised version of the Geothermal Catalogue. Importantly, temperature increases non-linearly with depth and so modelling would be required to estimate geothermal gradients with better accuracy. Nonetheless, this method enables estimations to be made in a simple way for a large data set.

$$\text{Geothermal gradient } (^{\circ}\text{C/km}) = \frac{(\text{measured temperature} - \text{surface temperature})}{\text{measurement depth}} \quad (1)$$

Once the geothermal gradient at each data point had been estimated, the average geothermal gradient for each council area could be established. The average geothermal gradient of a council area is taken to be the average of every data point within that council area as well as the data points outside that council area within 14 km. The 14 km radius around each point is derived from the average council area (km^2). This computation was made using GIS software.

The next step towards estimating the water temperature at 2 km and 4 km below the surface was to identify the council areas where aquifers are present at these depths. Again, GIS was employed to do so. Some 71 council areas in England and Wales contain an aquifer at 2 km, and 10 council areas contain an aquifer at 4 km. Notably, 6 council areas contain aquifers in-between these arbitrarily chosen depths, making them potential targets for council area heat networks, despite being excluded from the ranking system presented in the following section. This point is further considered in the discussion. The water temperature available for each council area is found by multiplying depth (either 2 km or 4 km) by average geothermal gradient, added to the surface temperature.

The top 30 council areas by aquifer temperature at a depth of 2km, and all 10 aquifers at a depth of 4km, are finally grouped by 3 confidence levels based off data availability. The council areas are then rank ordered by aquifer temperature whilst considering the population density of each council area as an approximate indicator of heat demand.

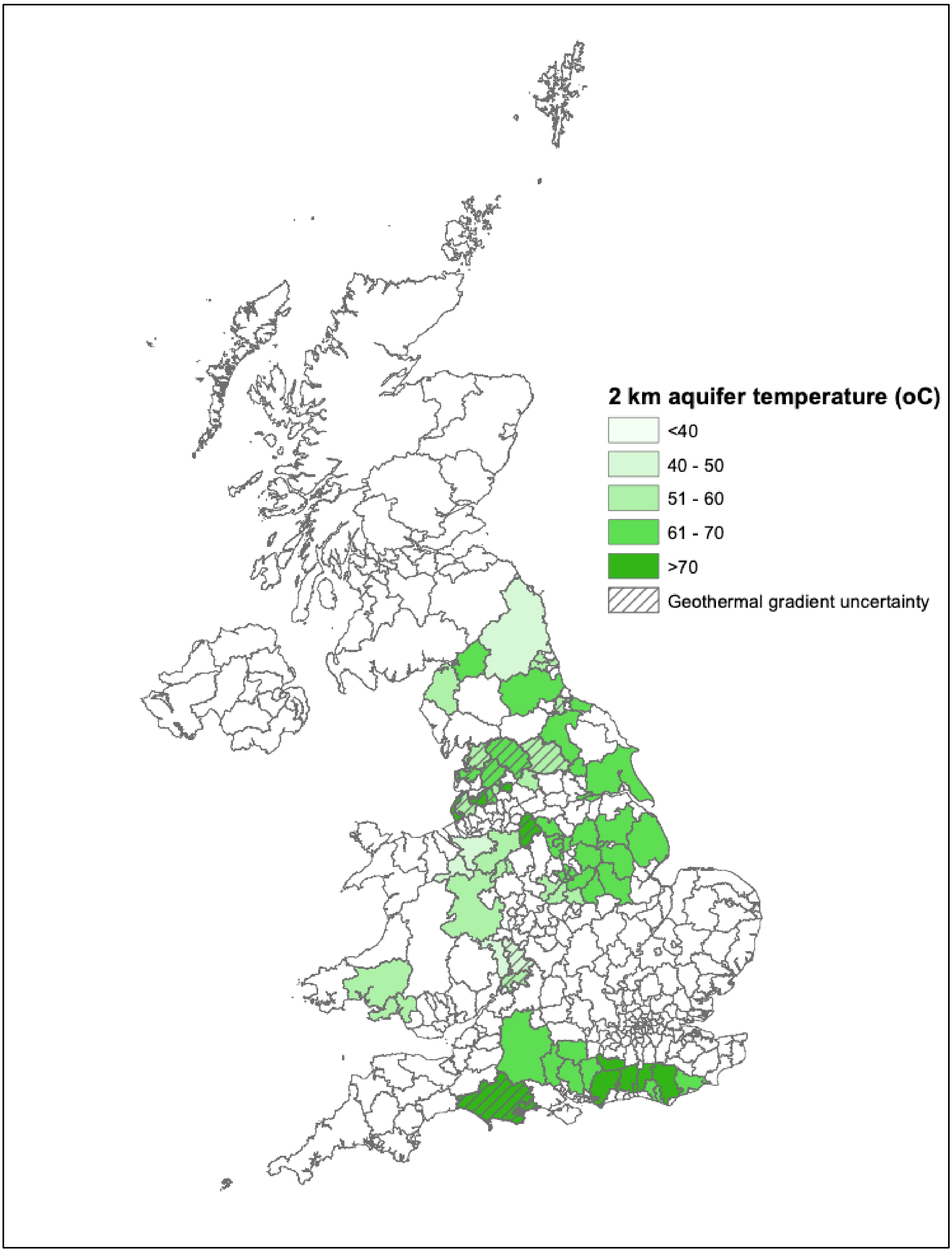

Figure 4 Council areas with a currently mapped aquifer at a depth of 2 km, scaled by estimated temperature (° C).

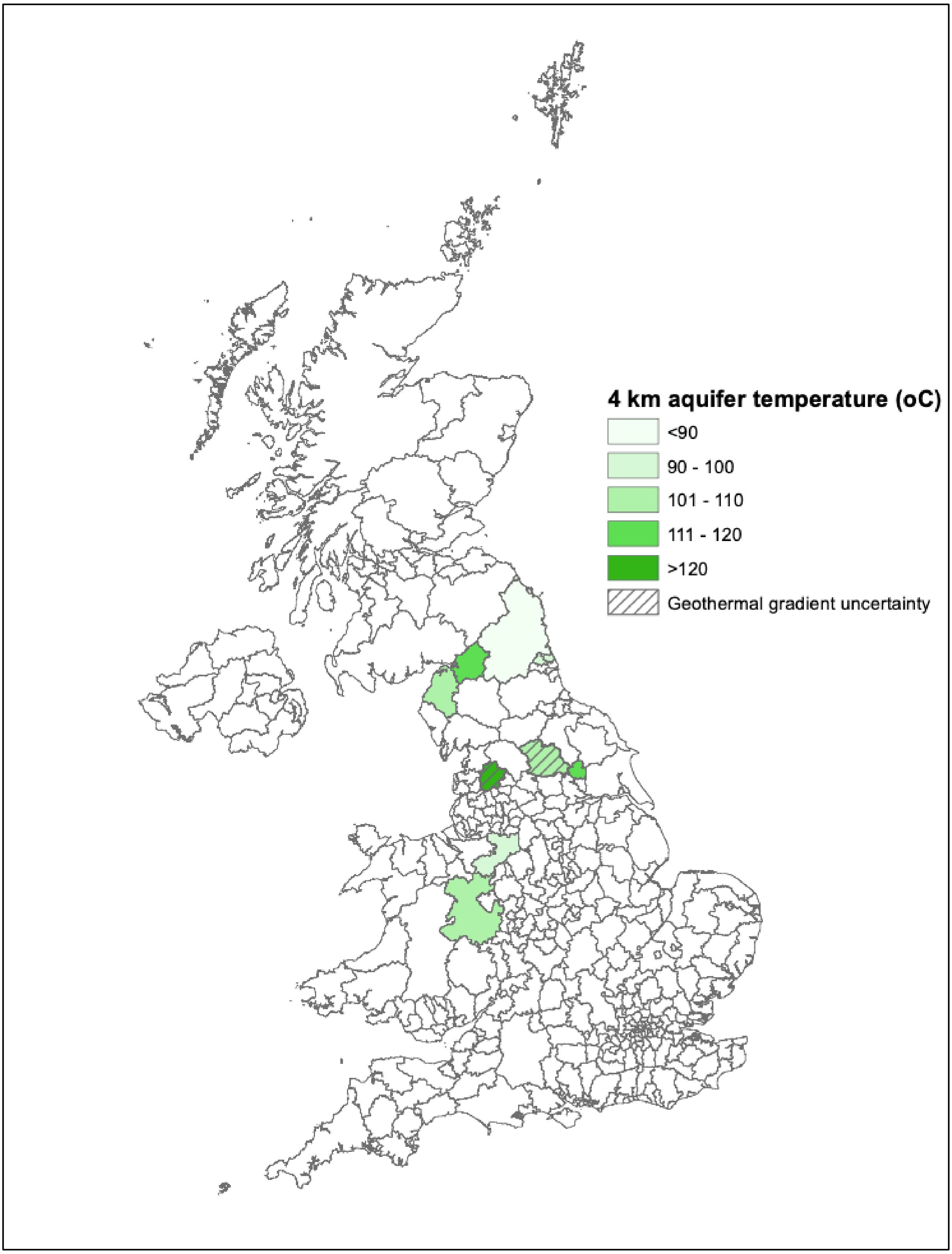

Figure 5 Council areas with a currently mapped aquifer at a depth of 4 km, scaled by estimated temperature (° C).

Figures 4 and 5 show the distribution of council areas containing aquifers at 2 km and 4 km, respectively. The water temperature available to each council area falls under one of 5 possible temperature ranges at each depth.

Connate water contained within porous rock at 2 km ranges from approximately 47 °C to 77 °C, reflecting variance in the average geothermal gradient from area to area. Carboniferous Limestone, Fell Sandstone and Border Group, Magnesian Limestone, Permian Sandstone, and Triassic Sandstone aquifers are all present at a depth of 2 km across England and Wales, covering a total of 71 council areas. Carboniferous Limestone aquifers are particularly prevalent at this depth, accounting for the target aquifer in over 70% of the 71 council areas.

Ten council areas have a probable sedimentary aquifer at a depth of 4 km or greater. Pore water at this depth ranges from 87 °C to 123 °C. Three of the 10 listed principal aquifers are present – Carboniferous Limestone, Permian Sandstone, and Fell Sandstone and Border Group. The latter is most common, covering all council areas of the northernmost cluster in England (Figure 5).

Council areas annotated with diagonal lines have additional uncertainty associated with the use of the average geothermal gradient to determine water temperature. Specifically, where no deep temperature measurement (>1000 m) has been recorded within a council area and its 14 km radius, the average geothermal gradient of that council area is only derived from shallower measurements. Uncertainty arises since the average geothermal gradient of each council area is used to project temperature at greater depths. Likewise, a deep measurement may exist, but the geothermal gradient calculated from this measurement falls below the average geothermal gradient of the council area. In either case, the water temperature values presented for these council areas may be more susceptible to an overestimation relative to their true values.

Council area	**Average geothermal gradient (°C/km)**	**Estimated water temperature at 2km (°C)**	**Population density (km^{-2})**	**Rank**
Bolsover	28	67	496	1
Newark and Sherwood	27	65	187	2
Bassetlaw	27	65	183	3
East Riding of Yorkshire	27	65	141	4
North Kesteven	27	65	126	5
West Lindsey	27	65	82	6
Rushcliffe	26	63	288	7
South Kesteven	26	63	150	8
Melton	26	63	106	9
North East Derbyshire	29	69	367	10
Nottingham	28	67	4437	11
East Hampshire	28	67	235	12
Winchester	28	67	188	13

Wiltshire	28	67	153	14
East Lindsey	28	67	80	15
Broxtowe	27	65	1414	16
Redcar and Cleveland	27	65	558	17
Test Valley	27	65	199	18
York	26	63	772	19
Hambleton	25	61	70	20
Wealden	33	77	192	21
Mid Sussex	31	73	448	22
Waverley	30	71	364	23
Horsham	30	71	268	24
Chichester	30	71	154	25
Chesterfield	28	67	1584	26
Sheffield	28	67	1583	27
Rother	28	67	188	28
Lewes	26	63	352	29
County Durham	25	61	237	30
Newcastle Upon Tyne	24	59*	2646	

*Additional uncertainty associated with use of the average geothermal gradient

Table 1 Thirty council areas ranked by confidence in the average geothermal gradient estimate, aquifer temperature at 2km, and population density

Council area	**Average geothermal gradient (°C/km)**	**Estimated aquifer temperature at 4km (°C)**	**Population density (km^{-2})**	**Rank**
Cheshire East	22	99	326	1
York	26	115	772	2
Shropshire	24	107	100	3
Carlisle	25	111	104	4
Newcastle upon Tyne*	24	107	2646	5
Allerdale	24	107	79	6
North Tyneside	21	95	2502	7
Northumberland	19	87	64	8
Ribble Valley*	28	123	103	9
Harrogate*	23	103	123	10

*Additional uncertainty associated with use of the average geothermal gradient

Table 2 Council areas ranked by confidence in the average geothermal gradient estimate, aquifer temperature at 4km, and population density

Council area	**Average geothermal gradient (°C/km)**	**Population density (km^{-2})**
Mansfield*	29	1419
Pendle	28	540
Eastbourne	27	2336
Brighton and Hove	26	3508
Middlesbrough	25	2608
Hartlepool	25	997

*Additional uncertainty associated with use of the average geothermal gradient

Table 3 Council areas with a probable sedimentary aquifer at a depth between 2 km and 4 km

Thirty council areas with the highest 2km aquifer temperature estimates and no additional average geothermal gradient uncertainty are presented in Table 1. All 10 council areas with aquifer temperature estimates at a depth of 4km are presented in Table 2. These two standalone depths are chosen so that the estimated supply to potential hot sedimentary aquifer (HSA) systems in each council area is fixed to a single variable, the average geothermal gradient.

Several measures are considered to rank-order the council areas by their potential geothermal resource. First is the number of data points (locations where temperature measurements have been made) used to determine the average geothermal gradient for each council area. Levels of confidence in the average geothermal gradient can be derived using this measure; In council areas with many data points, the average geothermal gradient is less likely to be an overestimation. Council areas are grouped into 3 levels of confidence, shaded from light to dark as confidence increases. The lower confidence group shows council areas where 10 or fewer data points have been used to calculate the average gradient, 11 - 49 data points represents medium confidence, and 50 or more data points represents greater confidence.

Within each confidence group, council areas are ranked by the estimated water temperature at each depth. Population density, a proxy for the heat demand of a council area, is used as a secondary measure to determine the rank-order where the estimated temperature is equal for more than one council area.

Six council areas have a probable sedimentary aquifer between 2km and 4km, along with available temperature data. Set out in table 3, these council areas also make potential settings for HSA systems.

Discussion

In this study, 18% of council areas across the UK have been estimated to have a potential hot water supply from two depths. The overall potential for geothermal energy supply via hot sedimentary aquifers across the UK, however, is much greater than this figure might suggest. A council area may only be analysed using the proposed methodology if both temperature data and aquifer depth data are available for that council area. While temperature data are available across most of the UK (Figure 3), the aquifer depth data used in this study only cover England and Wales. Nevertheless, council areas with the best potential hot water supply outside England and Wales can be anticipated using the estimated average geothermal gradient along with some knowledge of the subsurface. For example, Causeway and Coast Glens, the northernmost council area of Northern Ireland, has an estimated average geothermal gradient of 29 °C/km. Potential target formations may exist here, such as those within the Rathlin basin (an area explored for hydrocarbons). If a water-bearing formation of good transmissivity presides at depth in this basin, this council area could be a preferable target for a geothermal system. Council areas altogether lacking in temperature data highlight a need for increased exploration, particularly in areas adjacent to council areas with an estimated resource.

Figure 6 demonstrates the wide range of average geothermal gradient estimates across the council areas, from less than 20 °C/km to over 40 °C/km. The highest and lowest ends of this range are expectedly characterised by a low number of data points. Within some areas of low data point density (Figure 3), anomalously high or low temperature measurements perturb the estimated average geothermal gradient of several council areas at once, resulting in a clustering effect. Such anomalous temperature measurements may be the result of environmental, instrumental, or observational errors. This clustering effect can be observed in the South East of England, as exemplified by Figures 3 and 6. Of the 30 council areas ranked in Table 1, the 5 highest average geothermal gradient estimates are for council areas adjacent to one another in the South East (Figure 4). The high estimates for these council areas are mostly derived from the same few shallow measurements, and an anomalously high deep temperature measurement has been recorded in the area (thereby confirming the high average geothermal gradients, following the methodology). Specifically, a temperature of 52 °C was measured at a depth of 1.1km in the Bletchingly 2 well, resulting in an estimated geothermal gradient of 36 °C/km for that datapoint. Since these council areas are supported by 10 or fewer data points, they fall into the low confidence group. Without defining groups of confidence in the average geothermal gradient in this way, these 5 council areas would be ranked highest and the potential opportunity for deep geothermal energy could be overstated. Although some potential may exist, it is less certain, and further data acquisition is most crucial in these council areas (in addition to those council areas lacking in temperature data altogether).

Another example of the problems with small data sets associated with individual council areas is that of Newcastle Upon Tyne (Table 1) for which, the results of this study may underestimate the likely geothermal potential. The geothermal gradient of 24 °C/km was calculated using 5 data points. In central Newcastle the Science Central well (Helix) was drilled to 1.8 km in 2011 (Younger *et al* 2016) and the deepest temperature measured was from 1.74 km at 71 °C. However, the 5 data points also include one from Bolden Colliery with measured temperatures of around 25 °C at 1.4 km and thus a calculated geothermal gradient of about 10 °C/km. In this instance we are confident about the quality of the Science Central temperature value but wary of that from Bolden Colliery and in consequence it is almost certain that Newcastle upon Tyne's geothermal potential is here underestimated. Similar issues occur elsewhere in the dataset (see Bletchingly 2 above) but in many instances we do not have the knowledge to rank the quality of the various measurements.

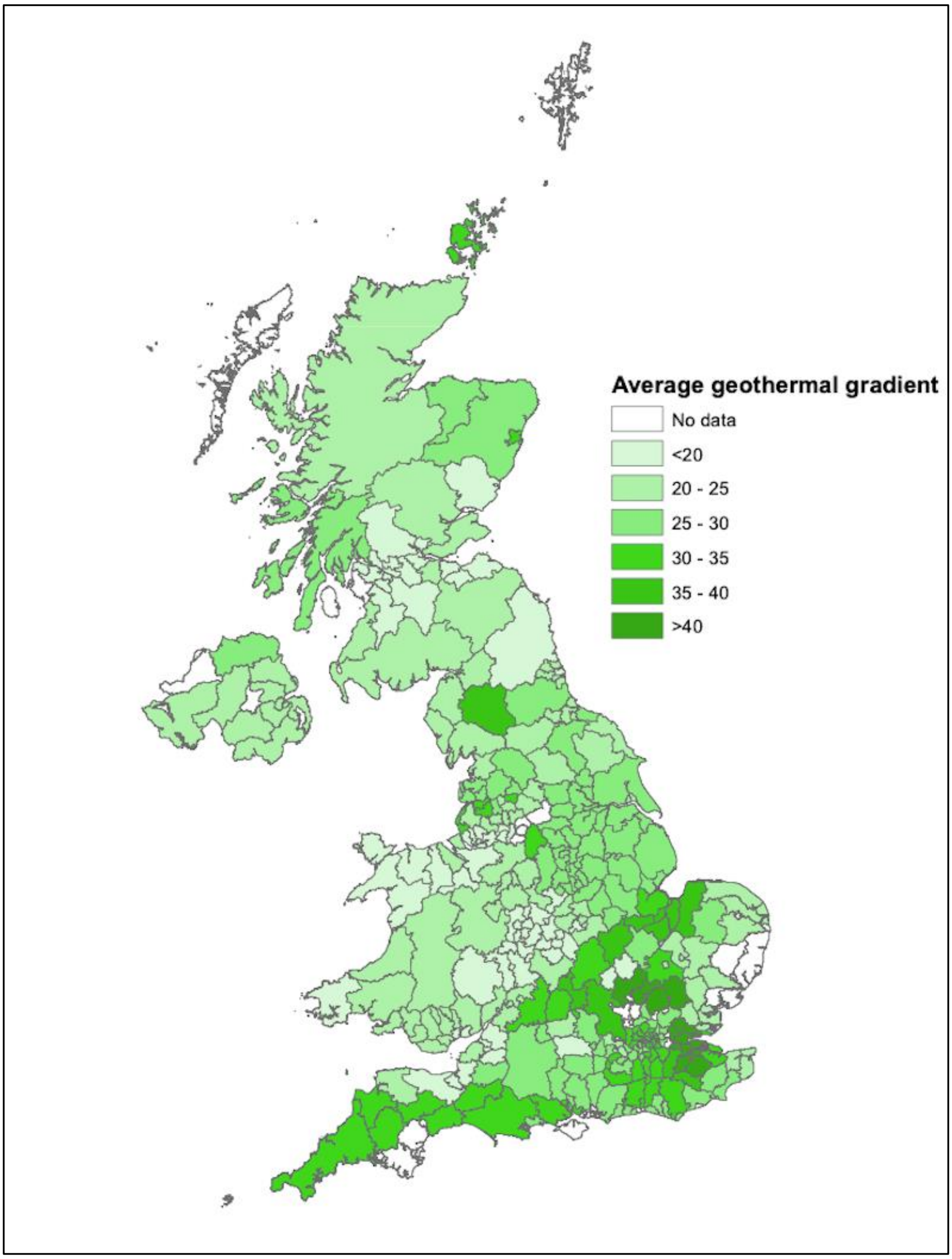

Figure 6 Calculated average geothermal gradient for council areas in the UK

Now considering the council areas estimated to have a potential hot water supply from aquifers found at depths of 2km and 4km, it is first noted that permeability must be sufficient to successfully deliver that hot water to the surface. In hydrothermal systems where suitable flow rates can be achieved, heat contained in aquifers can be made available for various uses via open loop well doublets. District heating is one such use, offering a much more efficient solution to space heating when compared with carbon-intensive gas boilers, which are currently widespread. Open loop well doublet systems are equally viable for industrial and agricultural application. Depending on the temperature of the resource and the desired application, a heat pump may be required to increase fluid temperature at the surface for it to become useful.

The correlation between population centers and the areas of higher geothermal potential is not serendipitous. The UK built is towns where it exploited the underlying rocks for water, for coal, for petroleum, for salt and a few other minerals which typically occur in sedimentary basins.

Limitations

To date, most assessments of the deep geothermal resource potential of the UK have been based off existing data collected for oil and gas exploration, supplemented with a limited number (<10) of dedicated geothermal exploration wells. More often than not, the existing data is not located in the same areas as high space heating demand. Therefore constructing reliable estimates of resource potential rely on interpolations. The methodology adopted here, while a simplification of the geological complexity of the UK, does enable a preliminary differentiation of areas where warm to hot water is likely to be distributed for use in direct heating applications.

Future Work

Going forward, to fully explore and exploit the potential of deep geothermal energy will require going beyond the status quo of adopting data previously acquired for oil and gas exploration (Ireland et al., 2021) and require the UK to pursue dedicated data acquisition programmes. This is becoming almost common place in Europe, where there have been tens of new dedicated geophysical surveys across cities in Germany, Belgium, Switzerland, and Austria to provide up to date and location specific data of the potential resource.

Making use of existing data in the UK is extremely challenged, this can be a barrier to entry for both large companies and SMEs alike. To maximize the UK's has a rich trove of existing data will require improving the accessibility of these data (Dickinson & Ireland, 2022). For geothermal energy, both the Netherlands and Germany have dedicated publicly available databases that underpin web-based access with the goal of supporting the advancement of geothermal energy. The UK should look towards these models and invest accordingly.

Finally, due to the nascent stage of geothermal exploration and development in the UK future efforts should include joint industry and public sector initiatives to focus on delivering the potential of deep geothermal in the UK.

As this report was being prepared a National Centre for Geothermal Energy Innovation is being formed with Durham University, Newcastle University, Shift Geothermal Limited and the Net Zero Technology Centre working together to obtain funds, plan structure and activity base as well as appoint to the centre and to an advisory board. The designation of the centre as one for 'Innovation' will ensure that its work will focus on translating the excellent research outputs from UK and other universities into a geothermal energy exploration taskforce as well as delivering operational geothermal energy systems to address both UK energy transition and energy security as well as delivering energy affordability in due course. The centre is anticipated to formally launch before end 2022.

Conclusions

The opportunity to exploit ultra-low carbon and sustainable geothermal energy in the UK to displace gas and improve energy security is highly significant. Here we have demonstrated that accessible geothermal energy occurs in many of the more populated areas of the UK and we have attempted to demonstrate this by displaying results of the geothermal analysis on a council by council basis.

The database upon which the calculations have been made is modest, approximately 1000 temperature measurements spread heterogeneously across the four countries of the UK. The quality of the data are difficult to assess. Some are very reliable other are likely to be erroneous.

Investment needs to be made to improve our understanding of the UK's deep subsurface and thus reduce the uncertainty which will accompany proposed geothermal exploration and developments and this enable geothermal energy to play a significant role in the UK's energy transition and deliver a secure, low-carbon energy future.

Acknowledgements

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