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Research Paper

# Geospatial analysis of unconventional geothermal resources and their potential role in decarbonising heat in Great Britain

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A B S T R A C T

This paper presents a geospatial analysis of Great Britain's unconventional geothermal resources considering their type, quality, and distribution with respect to heat demand. The investigation builds upon past assessments of geothermal heat in the study area by analysing the available resources alongside heat demand in an integrated and quantified manner on a 10 km$^2$ grid. By linking theoretical supply with practical demand, this work facilitates informed decision making towards increased uptake of decarbonised heat networks, which is a strategic priority for reducing emissions from UK residential buildings to net zero by 2050. To meet this goal, the market share of low or zero carbon heat networks is projected to need to rise to 20% from under 3% currently, with the present work directed at establishing the potential role of unconventional deep geothermal resources in delivering this growth. Practical resources are identified on the adopted 10 km$^2$ grid using a multi-criteria analysis of three types of map, namely, a geological map of suitable sedimentary aquifers and granite formations, a heat flow map, and a demand map. Verification of each map is pursued by comparisons with benchmarks from the literature. It is found that 9.8% of the study area has sufficient heating demand aligned with potentially exploitable unconventional geothermal resources, comprised of 83% hot sedimentary aquifers and 17% granite formations. Implementing geothermal heat networks in this 9.8% area could decarbonise up to 27% of Great Britain's overall heat demand, representing a considerable contribution towards the net zero target. By identifying specific areas where concentrated demand aligns with available deep geothermal resources, this work further underpins decision making towards technical and economic feasibility studies at a local level.

## 1. Introduction

Climate change mitigation and energy security have prompted renewed and increasing interest in developing and optimising low or zero carbon heat networks in the UK (Cowley et al., 2024; Davies et al., 2023; Reguis et al., 2021). Since residential space and water heating account for 21% of the UK's greenhouse gas emissions (BEIS, 2018), decarbonisation of this sector is key to reaching net zero emissions by 2050. As part of delivering this transition, there is a target to increase the heat market share of low or zero carbon heat networks to 20% from under 3% currently, encompassing growth in heat pumps, waste industrial heat, solar thermal, energy from waste, and deep geothermal heat (Department of Energy Security and Net Zero, 2023). In this context and building upon past geothermal exploration and resource assessments, this work presents a geospatial analysis of Great Britain's unconventional deep geothermal resources with an emphasis on matching heat supply and demand. The adopted methodology extends the theoretical capacity of geothermal heat in Great Britain, reviewed elsewhere (e.g. Gluyas et al., 2018), towards a practical capacity for low carbon heat networks. In this manner, the multi-criteria approach complements methodologies presented in the literature for various continental (e.g. Elbarbary et al., 2022), national (e.g. Al-Douri et al., 2019; Beckers et al., 2021; Dénarié et al., 2021; Mutombo and Numbi, 2019), and regional (e.g. Abuzied et al., 2020) contexts. Specifically in relation to the Great

*Nomenclature and abbreviations: d*, Heat demand expressed as a percentage of the grid box with highest demand (%); EGS, Engineered or enhanced geothermal system; GIS, Geographical information system; HSA, Hot sedimentary aquifer; OS, Ordnance Survey; OSGB, Ordnance Survey of Great Britain; RMSE, Root mean square error (m); WFS, Web Feature Service.

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Britain study area, the criteria applied in the present work leads to the first integrated and quantified geospatial analysis of the practical capacity for direct use deep geothermal heat networks.

Efforts to appraise the UK's deep geothermal resource have spanned decades, including studies by Rollin (1987), Downing and Gray (1986), Barker et al. (2000), Busby (2014, 2010), SKM (2012), Younger et al. (2012), Atkins (2013), Busby and Terrington (2017), and Gluyas et al. (2018). The UK's average geothermal gradient is 26 °C/km with a fairly uniform heat flow of 52 mW/m$^2$ in the basement rock (Downing and Gray, 1986). These values exhibit non-uniformity regionally and with depth based on hundreds of available measurements and estimates (Barker et al., 2000; Lee et al., 1987; Rollin, 1987; Rollin et al., 1995). Areas of anomalous heat flow lie within the background field of 52 mW/m$^2$, exceeding 120 mW/m$^2$ in the Southwest peninsula, 90 mW/m$^2$ in Northern England, and 80 mW/m$^2$ in the Eastern Highlands of Scotland, each due to granite batholiths. Values exceeding the background field also occur in Lincolnshire (East Midlands of England), Wessex (Southern England), the Midland Valley of Scotland, and Northern Ireland, associated with sedimentary basins where regional groundwater flow promotes upward heat transfer (Downing and Gray, 1986).

Deep geothermal exploration wells have been constructed in the UK since the 1970s, targeting sedimentary aquifers and Cornish and North Pennine (Weardale) granites. Wells have typically extended to 1–3 km with bottomhole temperatures of 69–100 °C (Younger et al., 2012). A deep well in Southampton has become operational, supplying a 1.7 MW$_t$ heat network using brine at 76 °C from an aquifer ranging between 1725–1749 m deep (Barker et al., 2000; Gluyas et al., 2020). Two deep geothermal energy projects are utilising the Cornish Granites. One of these projects is at United Downs near Redruth, where water to be produced at 175 °C with a circulation rate of 20–60 l/s will supply a 1–3 MW$_e$ binary cycle plant and heat network (Ledingham et al., 2019). Drilling was completed in 2019 with the production well extending to 5275 m and the injection well to 2393 m. Flow testing has been completed along with subsequent reservoir characterisation and investigation (Mahmoodpour et al., 2022; Reinecker et al., 2021). The second project underway in Cornwall is at Bodelva near St Austell. Drilling to 4.5 km has been completed targeting a zone of natural fractures. The well will initially deliver coaxial circulation and deliver heat to the nearby Eden Project (Abesser et al., 2023).

Besides specific exploration projects, Mesozoic era sedimentary basins offer a favourable balance of permeability and temperature for hydrothermal systems (Busby, 2014; Downing and Gray, 1986; Younger et al., 2012). Permian basal sediments are often included when defining these reservoirs, notably with regards to the Permo-Triassic sandstones and mudstones at depths exceeding 1500 m. The Mesozoic and Permian sedimentary basins are collectively referred to as post-Carboniferous and extend to depths of over 4 km in the Cheshire Basin and 2–3 km elsewhere (Atkins, 2013; Busby, 2014). Most temperature data for sedimentary aquifers is concentrated on these post-Carboniferous basins due to their association with onshore oil and gas exploration (Davies et al., 2014; Watson et al., 2020). Downing and Gray (1986) and Busby (2014) presented sediment stratigraphy including rock type, porosity, permeability, depth, thickness (and so intrinsic transmissivity), thermal conductivity, temperature, and geothermal gradient. Available aquifer models of post-Carboniferous basins are conceptually simple but rely on sufficient and accurate data for statistical or deterministic estimation of heat in place. Only reservoirs that meet or exceed a cut-off temperature are considered and heat in place is based on the theoretical potential to uniformly reduce the temperature to a certain baseline, typically a post-use return temperature. Busby (2014) collated findings from several such studies on the UK's post-Carboniferous basins (e.g. Downing and Gray, 1986; SKM, 2012), reporting a heat in place of 201–328 EJ compared to the total UK annual energy consumption of around 6 EJ.

There have also been efforts to characterise the geothermal potential of the Upper Palaeozoic (Carboniferous and Devonian period) basins and basement rocks, although less data is available (Busby and Terrington, 2017). Gluyas et al. (2018) collated properties including sediment thickness, geothermal gradient, and maximum temperature for the UK's main onshore sedimentary basins, including Upper Palaeozoic basins. The Upper Palaeozoic rocks may be metasedimentary with the expectation of low porosity and permeabilities less than $1 \times 10^{-14}$ m$^2$ (Busby, 2014), with basement rock becoming less porous and less permeable. Effective heat recovery then depends on development of an engineered geothermal system (EGS) through technical enhancement, possibly including the supply of a working fluid and/or the creation or enhancement of a fracture network (Breede et al., 2015). The definition of EGS can tentatively be expanded to include cases where heat recovery depends on naturally fractured zones in otherwise conduction-dominated low permeability reservoirs. Such zones are known to exist in Upper Palaeozoic sediments, evidenced by warm water springs at locations including Bath, where heated groundwater rises through fractured Carboniferous Limestone (Barker et al., 2000).

It is evident that the UK offers widespread regional potential to explore heat contained within granites and post-Carboniferous sedimentary basins. The geothermal potential of Carboniferous and Devonian sediments together with the basement rocks has been given less attention, mainly due to a lack of data and the likelihood of low permeability. Whilst several studies have assessed the conditions required to make a geothermal resource technically feasible in the UK, these existing assessments have not included an integrated and quantified analysis of heat demand. This is an important gap in the literature since proximity of source and demand constrains the efficiency and economic viability of a heat network.

Busby (2014) and Gluyas et al. (2018) presented maps of areas of potential supply intersecting with areas of heat demand based on heat maps published by the government, but did not explicitly address the question of demand as part of the analysis. The present study builds upon findings of previous assessments by analysing the available resources alongside heat demand on a 10 km$^2$ grid. Besides expanding knowledge in relation to the Great Britain case study considered, a more general contribution of the present work is a workflow for linking assessments of heat in place with heat demand based on building footprint and altimetry data. Input data is collected and analysed to produce three types of map: (1) a geological map of suitable sedimentary aquifers and granite formations, (2) a heat flow map, and (3) a demand map. Verification of each map is pursued by comparisons with various benchmarks from the literature. A multi-criteria approach is adopted accounting for each map to establish the distribution of geothermal heat network potential in the study area. Prioritisation is then achieved by considering additional metadata.

The paper is structured as follows: the geospatial workflow is explained in terms of data collection and processing for heat demand, geothermal resource distribution, and heat flow. The resulting maps are next presented and discussed individually alongside verification using appropriate benchmarks, followed by discussion of the multiple criteria applied for the geospatial analysis. Finally, the results of the analysis are presented and discussed by region, leading to the conclusions of the work. This work is an important advance towards understanding the practical potential of deep geothermal heat networks in contributing to heat decarbonisation in the UK, which is a strategic priority as part of reducing emissions from residential buildings to net zero by 2050.

## 2. Geospatial analysis workflow

QGIS Version 3.16.1 was used for this investigation. This section presents the datasets and processing steps used to generate the demand map, resource map, and heat flow map. A rule-based analysis is performed on a 10 km$^2$ grid to determine and prioritise areas with the greatest potential for geothermal heat networks. The geospatial criteria applied to perform the analysis are also presented in this section. The final output is a list of areas with sufficient demand and potential direct use geothermal resources, with metadata for use in prioritisation. A

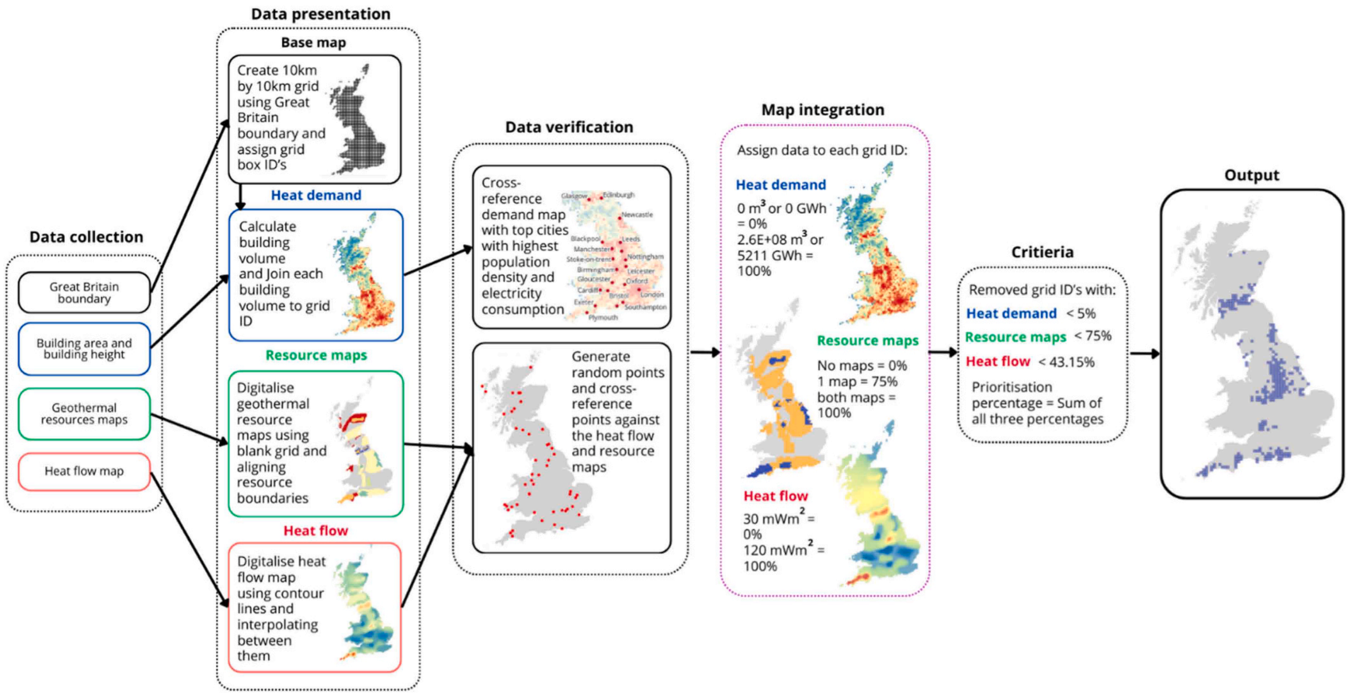


**Fig. 1.** Graphical summary of the workflow applied for the geospatial analysis, which can be cross-referenced with the detailed steps described in Sections 2 and 3.

**Table 1**
Summary of datasets used in this study and associated limitations.

| Dataset | Format | Source | Notes |
|---|---|---|---|
| Great Britain Boundary | Shapefile (Polygon) | European Environment Agency | |
| MasterMap Building Area | Shapefile (Polygon) | Ordnance Survey (OS) | This dataset is updated every 6 months – this work adopts data from the October 2022 update. The accuracy of polygons is detailed in Table 2. |
| Building Height | Shapefile (Point) | Ordnance Survey (OS) | This dataset is updated every 6 months – this work adopts data from the October 2022 update. The lidar data used has ± 10 mm vertical accuracy. |
| Geothermal Map of United Kingdom | Map | British Geological Survey | Available under Open Government Licence. Published in 1985. Digitising data from a map may introduce a degree of inaccuracy. |
| UK Sedimentary Basins and Granite Batholiths | Map | Gluyas et al. (2018) | Digitising data from a map may introduce a degree of inaccuracy. |
| Heat Flow in the UK | Map | Busby (2010) | Digitising data from a map may introduce a degree of inaccuracy. Map categories have broad ranges. |

graphical summary of the workflow described in this section is provided in Fig. 1 and can be cross-referenced with the approach described below.

### 2.1. Data collection

All datasets and sources used for this study are listed in Table 1 and illustrated in the left-hand panel of Fig. 1. Most datasets were provided

**Table 2**
Accuracy of the MasterMap polygon datasets. Absolute accuracy reflects how closely the coordinates of a point in the dataset agree with the coordinates of the same point on the ground in the British National Grid reference system. Relative accuracy reflects positional consistency of a data point in relation to other local data points. RMSE is the root mean square error.

| Original survey scale | 99 % confidence level | 95 % confidence level | RMSE |
|---|---|---|---|
| 1 : 1250 | | | |
| Absolute accuracy | 0.9 m | 0.8 m | 0.5 m |
| Relative accuracy | ±1.1 m (up to 60 m) | ±0.9 m (up to 60 m) | ±0.5 m (up to 60 m) |

in an ESRI Shapefile format, ready to use in QGIS. To avoid duplicating the analysis of geological data pertaining to the distribution of geothermal reservoirs and heat flow, this study employs previously published maps by Busby (2010) and Gluyas et al. (2018). This study was carried out on the Great Britain land area as datasets used only covered this area. Table 2 summarises the accuracy of the OS MasterMap used to determine building area. At the adopted scale of 1:1250, this input data is deemed to carry an appropriate level of accuracy for the 10 $km^2$ grid used in this work.

### 2.2. Data processing

The project coordinate reference system (CRS) is set to OSGB 1936/ British National Grid (ESPG 27700), which is standard for geospatial analysis in the UK. Distance and area units are in m and $m^2$, respectively. Raw datasets were imported into the project as vector data in a Shapefile format. After the file was imported into the project and pre-processed, it was exported as a Geopackage format. The Great Britain Boundary (i.e. the study area boundary) needs no pre-processing and was immediately exported as a Geopackage. The study area was split into a 10 $km^2$ grid, which is viewed as an appropriate geospatial resolution at the national scale, balancing constraints imposed by: (1) the resolution of input data for heat flow and geothermal resource availability, (2) computational

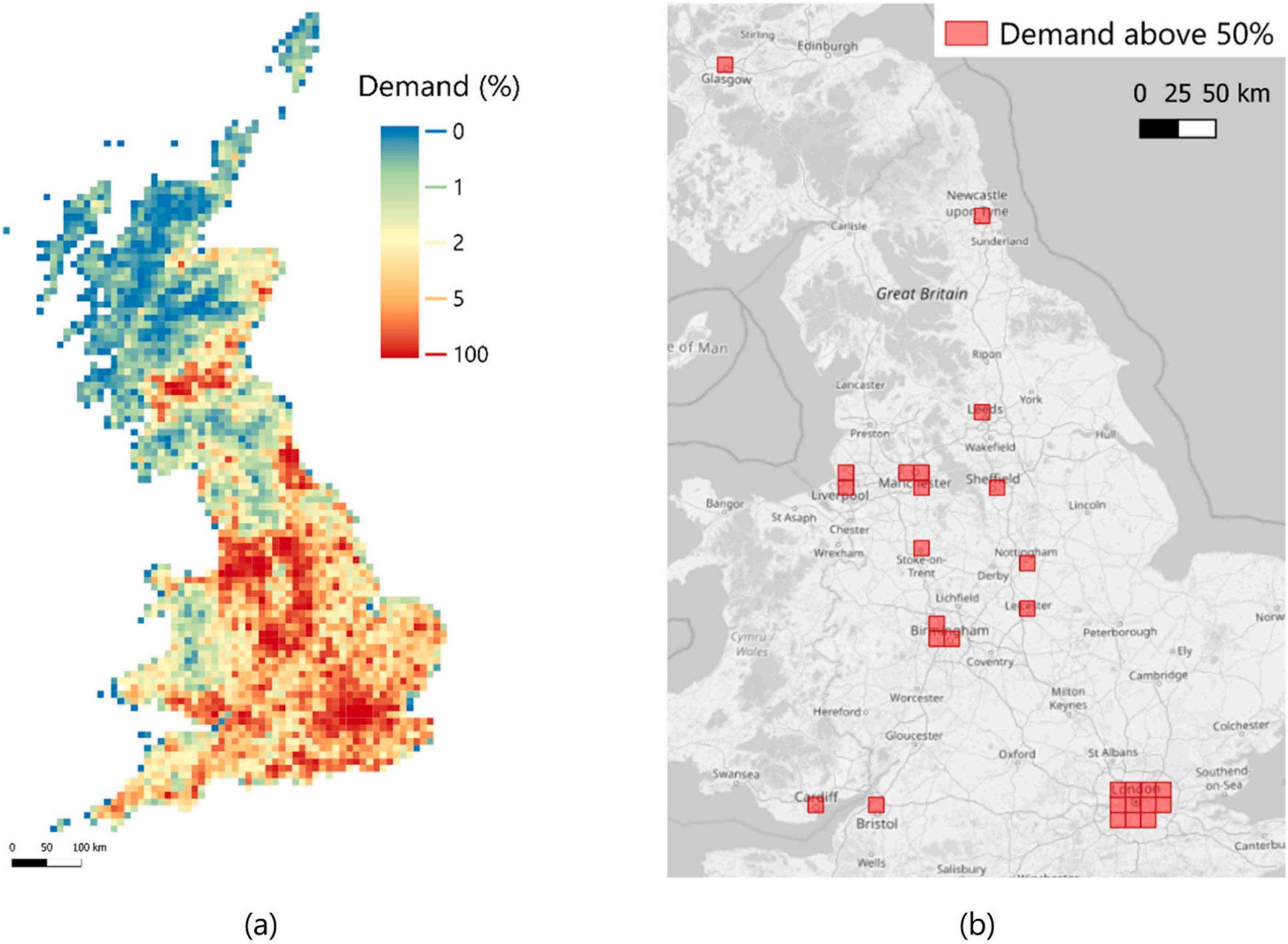


**Fig. 2.** Heat demand maps (a) for 10 km$^2$ grid boxes expressed as a percentage of the grid box with maximum heat demand, and (b) for grid boxes with demand exceeding 50% of the grid box with maximum heat demand.

effort for analysing the large datasets for joint assessment of heat supply and demand, and (3) retention of a sufficiently fine grid that can, to a reasonable extent considering points (1) and (2), distinguish nonuniform heat demand density associated with small- and medium-sized towns. In general terms, a 10 km$^2$ grid size facilitates national screening that can inform the strategic selection of local areas for site specific investigation. In this sense, the present study is not performed at a resolution that can inform specific requirements for infrastructure, risk management, environmental impact, or other such factors that can only be accurately assessed at regional or local scale. Nonetheless, in relation to point (3), the suitability of the selected grid size is evaluated quantitatively in the data presentation and verification section. The steps taken to process and present the data are summarised in Fig. 1 and explained in the following sections for each of the heat demand, geothermal resource, and heat flow maps.

### 2.2.1. Heat demand map

To understand where areas of high heat demand levels are concentrated, a demand map was created. This map was created assuming that all buildings have equal energy efficiency ratings, meaning the building volume is directly correlated to demand. A 2D layer of building area conjunction and a dataset that states buildings heights from datum were used to create a building volume. This dataset was then joined by location to the associated grid box layer and summed by grid box ID to create a building volume for each box. The OS MasterMap was imported as a Web Feature Service (WFS). The option to load a WFS is under the Open Data Source manager: a new server connection was added using the following application programming interface (API):

https://api.os.uk/features/v1/wfs?key=37nVAIWLKnNX1qHXIHVZ6NPJJZ5oZ3a.

After making the connection, the feature titled *'Topography_TopographicArea'* was selected and added to the layer panel. This layer was exported as a Geopackage to then be edited. The following sets out the steps taken to create the demand map:

1. Create and export as a layer 2D building areas by filtering the 'Land use' field to 'Buildings'.
2. Create and export building height data at points aligned with OS MasterMap building polygons.
3. Join building height with building area with a one-to-one match to obtain building volume.
4. Join each building volume to nearest grid centroid with maximum nearest neighbours set to one. Buildings over a border join with the nearest point and are assumed to be fully in that grid box. Grid IDs with zero demand were deleted as these were areas not on land or with no buildings.

### 2.2.2. Geothermal resource map

Maps by Busby (2010) (heat flow) and Gluyas et al. (2018) (resource type) as well as the British Geological Survey's Geothermal Map of the United Kingdom were digitalised using reference points. The BGS map illustrates boundaries of geothermal resources in Permian and Triassic sedimentary basins, other Mesozoic basins, and incrop and outcrop granites characterised by heat production greater or less than 4 μW/m$^3$. This map is a more conservative estimate of sedimentary basins and geothermal resource locations compared to the map by Gluyas et al. (2018). Both maps were created from the same deep borehole data and 3D geology, but one has made more conservative assumptions on resource boundaries. This work takes account of areas intersecting both estimated boundaries. For the final map, boundaries carried forward include the Permian and Triassic sedimentary aquifers and granites from the BGS Geothermal Map and all resource boundaries from the map by Gluyas et al. (2018). To digitalise the resource maps, a blank grid was placed over the map, aligned to the grid and mapped on QGIS using a line feature to create each boundary. The split with lines tool was then used to split the study area (input layer) with the identified resources (split layer). A resource type and map reference were added to each polygon.

#### 2.2.3. Heat flow map

Previously published heat flow maps (Busby, 2014; Downing and Gray, 1986; Gluyas et al., 2018) provide a visualisation of heat flow with 10 mW/m$^2$ increments based on 3D geology and extensive deep borehole data. Linear interpolation of contour lines was employed to create a more granular range of heat flow values for analysis. To digitalise the map, the heat flow contours by Busby (2014) were drawn in a new Shapefile line heat flow layer. TIN (Triangular Interpolation Network) interpolation was used to linearly interpolate values between these contour lines, clipped to the study area to create a raster heat flow map. The raster to points tool was used to plot a point for each raster pixel with a heat flow value. This point dataset (input layer) was then joined by location to the grid centroid layer.

### 2.3. Geospatial analysis criteria

Considerations were made when calculating what areas have sufficient demand to justify a geothermal district heat network and how densely populated an area would have to be to deem it economically viable. It was assumed that one deep geothermal district heat network can supply upwards of 40 GWh per year, which is based on existing networks. The building volume of each grid box divided by the maximum grid box building volume was applied to obtain heat demand percentages. A minimum heat flow rate of 50 mW/m$^2$ is typically required for deep geothermal systems that are intended for direct heat applications (IEA, 2011). Prioritisation of options is based on heat demand percentage, heat flow, and intersection with one or both resource maps based on the following criteria:

1. Heating demand of 5% or more.
2. Heat flow of 50 mW/m$^2$ or more.
3. Intersection with available geothermal resources.

Criterion 3 is applied to remove grid boxes not intersecting a suitable geothermal resource as identified by the British Geological Survey's Geothermal Map of the United Kingdom or Gluyas et al. (2018). As summarised in Fig. 1, grid box prioritisation is pursued by summing percentage values arising from each criterion. Specifically, this prioritisation comprises: heat demand as a percentage of the grid box with highest demand provided this exceeds the 5% cutoff, intersection with one (75% weighting) or both (100% weighting) geothermal resource maps, and heat flow as a percentage of the peak value of 120 mW/m$^2$ provided this exceeds 43.15%, which is defined by a cutoff heat flow of 50 mW/m$^2$ relative to the peak heat flow of 120 mW/m$^2$.

## 3. Data presentation and verification

For ease of data comparison and processing, data for heat demand, geothermal resource distribution, and heat flow are each considered using the aforementioned 10 km$^2$ grid. Before presenting results of the multi-criteria analysis, it is important to consider the trends and verification of each data set distinctly.

**Table 3**
Summary of percentage heat demand by grid box.

| Demand percentage, *d* (%) | Number of grid boxes | Percentage of grid boxes (%) |
|---|---|---|
| $d > 75$ | 7 | 0.25 |
| $50 < d \leq 75$ | 21 | 0.75 |
| $25 < d \leq 50$ | 90 | 3.24 |
| $d < 50$ | 2664 | 95.76 |

### 3.1. Heat demand map

A percentage value was assigned relative to the grid box with highest demand (5211 GWh). The resulting heat demand map is shown in Fig. 2a. As expected, major cities populate the grid boxes with a demand value over 50%, as shown in Fig. 2b. These cities all appear in the Office of National Statistics top 20 subnational electricity consumers in 2021 and the top 17 cities by population density, hence it can be concluded that these findings are logical and consistent with related metrics.

Table 3 shows that most grid boxes (95.76%) have a heat demand less than 50% of the grid box with greatest heat demand, which is perhaps not surprising given that this benchmark is situated in central London. Considering the prevalence of grid boxes with lower heat demand and the grid box size of 10 km$^2$, it was appropriate to examine the distribution of demand within these grid boxes to ensure that available heat can be linked to concentrated demand with greater confidence. A low heat demand for a 10 km$^2$ grid box has the potential to be uniformly or nonuniformly distributed. A grid box with low and uniformly distributed heat demand is more likely to have reduced techno-economic potential due to the requirement for more distribution infrastructure with associated thermal losses. Conversely, a grid box with low and nonuniformly distributed heat demand can be expected to have areas of elevated heat demand density (i.e. larger towns and villages) that may improve the techno-economic potential. With this in mind, 10 random grid boxes with between 5–10% demand were selected, and it was found that over 90% of building volume tended to be concentrated in two or three 1 km$^2$ areas, with the remaining area occupied by open space. The inferred heat demand density of grid boxes with 5–10% demand helps to justify the adopted criterion for a heat demand ≥ 5% of the grid box with greatest heat demand. Further analysis showed that grid boxes exceeding 10% heat demand all have significantly populated areas with good candidacy for a heat network.

### 3.2. Geothermal resource map

Fig. 3 shows the final resource map. This map fulfils an important role in the geospatial analysis by implicitly considering a large amount of existing information on the distribution of viable geothermal reservoirs. Areas outside of these boundaries are therefore expected to have a higher likelihood of being unsuitable with unfavourable geological conditions for direct heat applications. A tool that generates 50 random points was used over the whole map and manually cross-referenced with reference maps to verify input map results. These 50 points serve to validate a set of randomly generated locations against the map to gain confidence that a grid box is accurately returning its available resource.

### 3.3. Heat flow map

The final heat flow map is presented in Fig. 4. Although borehole locations were plotted in the original heat flow map, any data relating to these was not published and they were subsequently not able to be used to validate the accuracy of this map. In order to check the validity of the

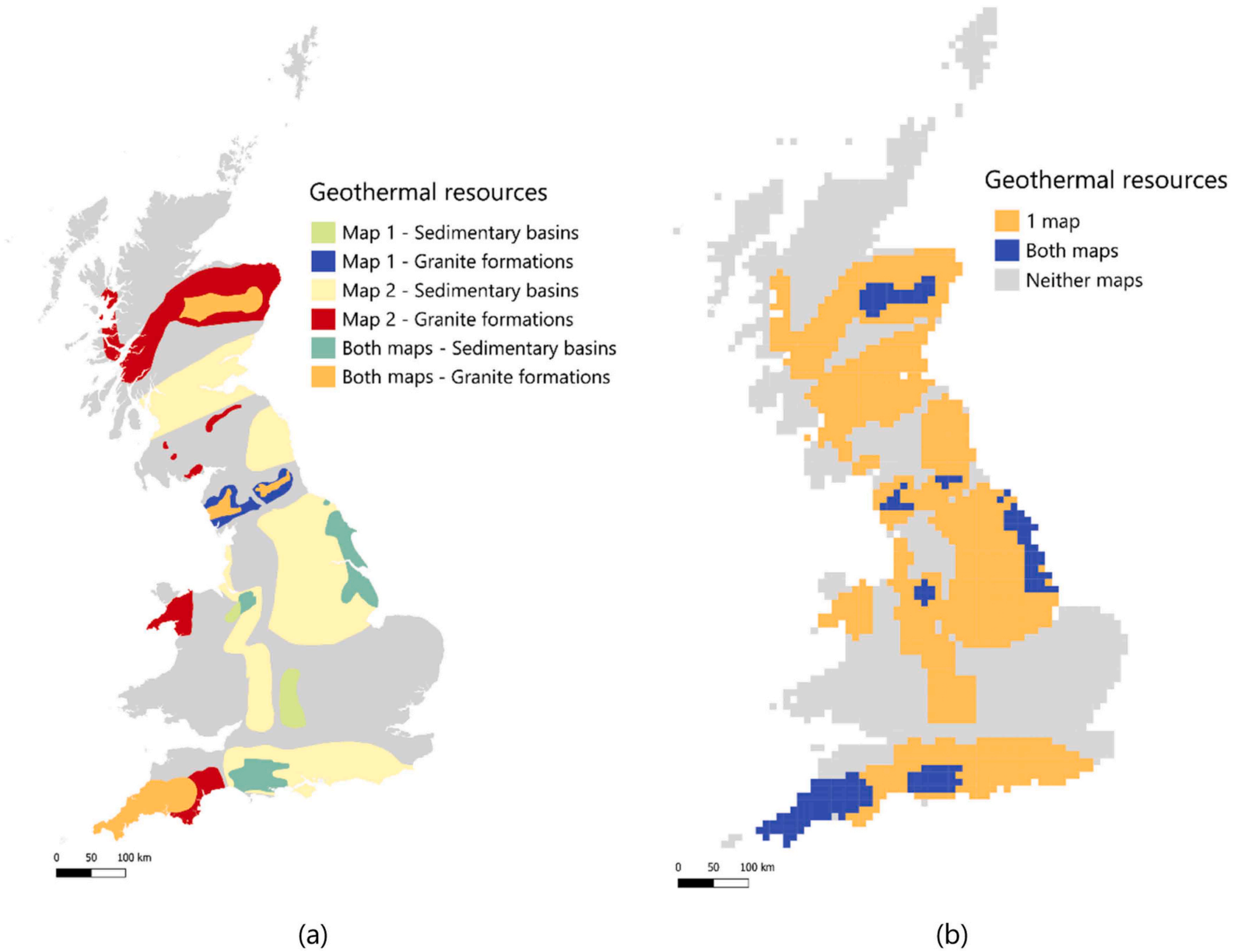


**Fig. 3.** Geothermal resource maps showing (a) identified geothermal resources based upon the BGS Geothermal Map and the map by Gluyas et al. (2018), and (b) transposition of the resulting map onto the analysis grid.

heat flow map, measured heat flow values calculated from specific boreholes discussed in the Geothermal Catalogue of the UK (Rollin, 1987) are cross-referenced in Table 4 to the average heat flow values applied to the grid in this study. Slight variations in measured and average heat flow values could be due to inaccuracies caused by averaging grid box heat flow values or transposing the map.

A successful exploitation of geothermal resources in Southampton has a heat flow value of 60 mW/m$^2$, which is considered near average for the UK. However, Newcastle city centre, identified as having an average heat flow of 82.84 mW/m$^2$, recently underwent drilling of a 2 km deep borehole for direct-use heating and was unsuccessful due to insufficient flow rate. It is apparent that heat flow alone cannot characterise geothermal potential and that reservoir transmissibility should be considered where possible. However, such data is somewhat limited across the study area and so is not included in the present geospatial analysis. Heat flow data is nonetheless useful in predicting resource suitability and the minimum heat flow criterion was set for the analysis to reduce the likelihood of unsuccessful options in the output. A minimum value of 50 mW/m$^2$ was assumed in this analysis for a resource to be viable, however higher values are favourable and score higher in prioritisation.

## 4. Geospatial analysis outcomes

To create a list of areas with greatest potential for geothermal heat networks, each map was analysed based on the established minimum value criteria. Prioritisation of this list was carried out to determine areas with greatest potential for further exploration and development. The results from this rule-based analysis are shown in Fig. 5. This analysis indicates that 9.8% (237 of out 2782 grid boxes) of the study area has deep geothermal energy supply potential aligned with sufficient heat demand. Of this, 83% are associated with sedimentary aquifers and 17% with granite formations. The total heat consumption for Great Britain in 2022, domestic and otherwise, was 2.736 EJ and the area covered by this output makes up 27% of this (0.74 EJ). These results are further explored in a regional context in the following sections.

### *4.1. Southwest England*

Fig. 6 focuses on the output for Southwest England. Major cities with populations exceeding 100,000 have been plotted; other cities, towns, and densely populated areas with sufficient demand are also covered in this output. Prominent resources in this region lie in Mesozoic sedimentary rocks of the Sherwood Sandstone Group in the Wessex basin, indicated by the eastern clusters on the south coast, and the granites extending across Cornwall and Devon, indicated by the western clusters

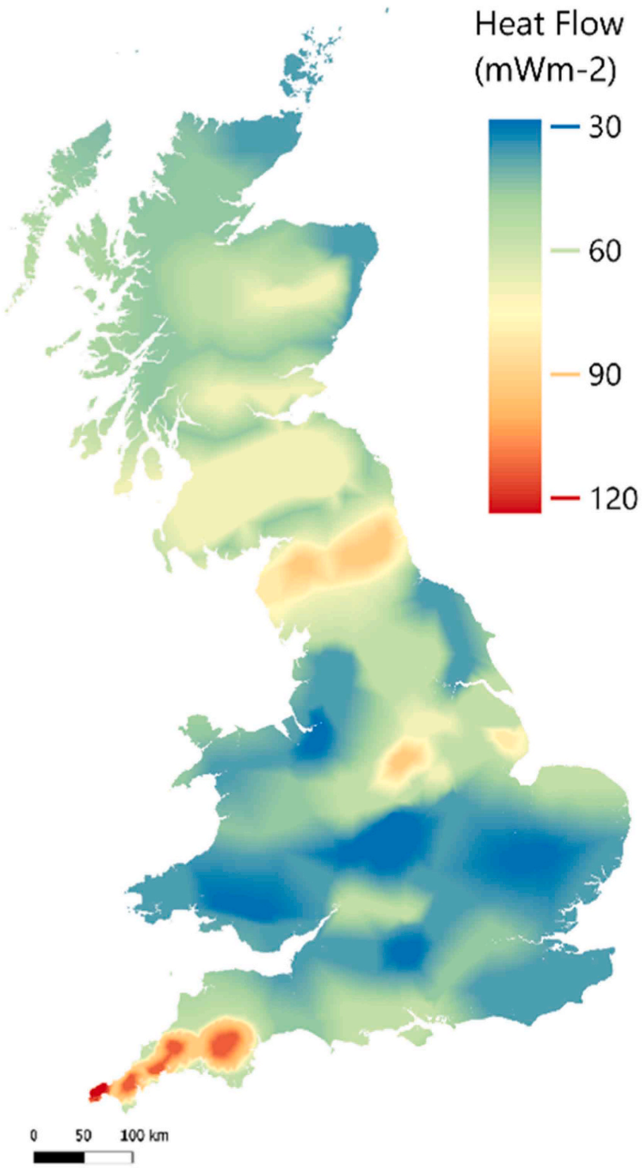


**Fig. 4.** Heat flow map of the Great Britain study area with 10 mW/m$^2$ increments based on previously published geological and deep borehole data (Busby, 2014; Downing and Gray, 1986; Gluyas et al., 2018).

**Table 4**
Comparison of heat flow values applied in this study to measured values reported by Rollin (1987).

| Grid ID | Location | Measured heat flow (mW/m$^2$) | Present heat flow (mW/m$^2$) | Difference (mW/m$^2$) |
|---|---|---|---|---|
| 5965 | Southampton | 60 | 60 | 0 |
| 5245 | Aberdeenshire | 29 | 33 | 4 |
| 2462 | Rosemanowes | 110 | 110 | 0 |
| All boxes | Study area | 68 | 64 | −4 |

on the south coast. The Sherwood Sandstone Group holds good HSA prospects, which are thought to be more favourable towards the west (Downing and Gray, 1986). Faults in the granites in the western section are appealing for EGS, evidenced by recent developments at United Downs and Bodelva. Grid boxes with the highest heat flow values from this study all occur in Cornwall in areas underlain by this granite, as summarised in Table 5. The locations of successful geothermal projects can be seen to align with the output. The two points west are the United Downs and Bodelva projects, whilst the eastern point is the Southampton geothermal project.

### 4.2. The Midlands and Northern England

The output of the analysis in the Midlands and Northern England is shown in Fig. 7. The main section of the Midlands is underlain by Mesozoic and late Palaeozoic sedimentary rock, predominantly comprising Devono-Carboniferous strata, whereas the northern cluster of grids includes the North Pennine Batholith (Weardale Granites) extending northwards towards the Northumberland Trough sedimentary basin of Carboniferous age (Gluyas et al., 2018). Two successful geothermal projects and major cities with a population over 100,000 intersecting with this output have been plotted. The Weardale borehole in Eastgate, drilled in 2004, was deemed successful for direct heat use. The brine produced from the well was also found to contain high amounts of lithium that are being extracted for use, but the borehole has not yet been used for direct heat purposes, arguably due to its distance from significant demand, reflected in this study since the project lies outside of the identified grid boxes.

It is noted that many of the identified grids in the Midlands are also underlain by flooded mine workings, possibly offering an alternative heat source. Although further analysis of this potential is beyond the scope of the present work, projects taking advantage of abandoned mines near Newcastle, Nottingham, and Sheffield are currently in planning or being implemented.

### 4.3. Scotland

Fig. 8 shows the output of this study in Scotland, concentrated in the Midland Valley. The Midland valley has the highest prospects for HSA as it is underlain by a Devono-Carboniferous sedimentary basin (Gluyas et al., 2018). The more isolated northern-most grid boxes are associated with the radiothermal Caledonian granites of the Eastern Highlands (Downing and Gray, 1986) associated with heat demand in the vicinity of Aberdeen, Elgin, and Inverness. Scotland was significantly affected by glaciations during the last ice age which has had lasting effects on the geothermal gradient to a depth of 2 km. Corrections to heat flow estimates made in the latest version of the BGS's Geothermal Catalogue of the UK have not yet been updated to factor this and Scotland's geothermal resource potential below the climate-affected zone has subsequently been underestimated in the literature.

### 4.4. Discussion and prioritisation

Having met the resource selection criteria for heat flow and resource availability, it can be assumed that heat networks would be economically viable in grids with high heat demand. This may be true in terms of increased capacity, increased flexibility for deployment, or both. Aligned with the novel contribution of the present work for geospatial analysis of geothermal heat networks with a focus on demand, Table 6 presents a subset of five grid boxes with highest heat demand. Existing literature addresses the importance of proximity for heat networks but does not substantially link heat demand to potential supply. This study significantly improves upon this by running a rule-based analysis on 10 km$^2$ grid boxes based on demand, heat flow, and resource availability. All grids identified from the resulting analysis, shown in Fig. 5, meet the selection criteria and should be prioritised for further investigation. In effect, the present work has identified that 237 of out 2782 10 km$^2$ grid boxes in the Great Britain study area have deep geothermal energy supply potential aligned with sufficient heat demand.

Gluyas et al. (2018) presented a conservative estimate of 200 EJ of accessible heat in the resources included in this work. Considering that the identified grid boxes account for 27% of Great Britain's heat demand

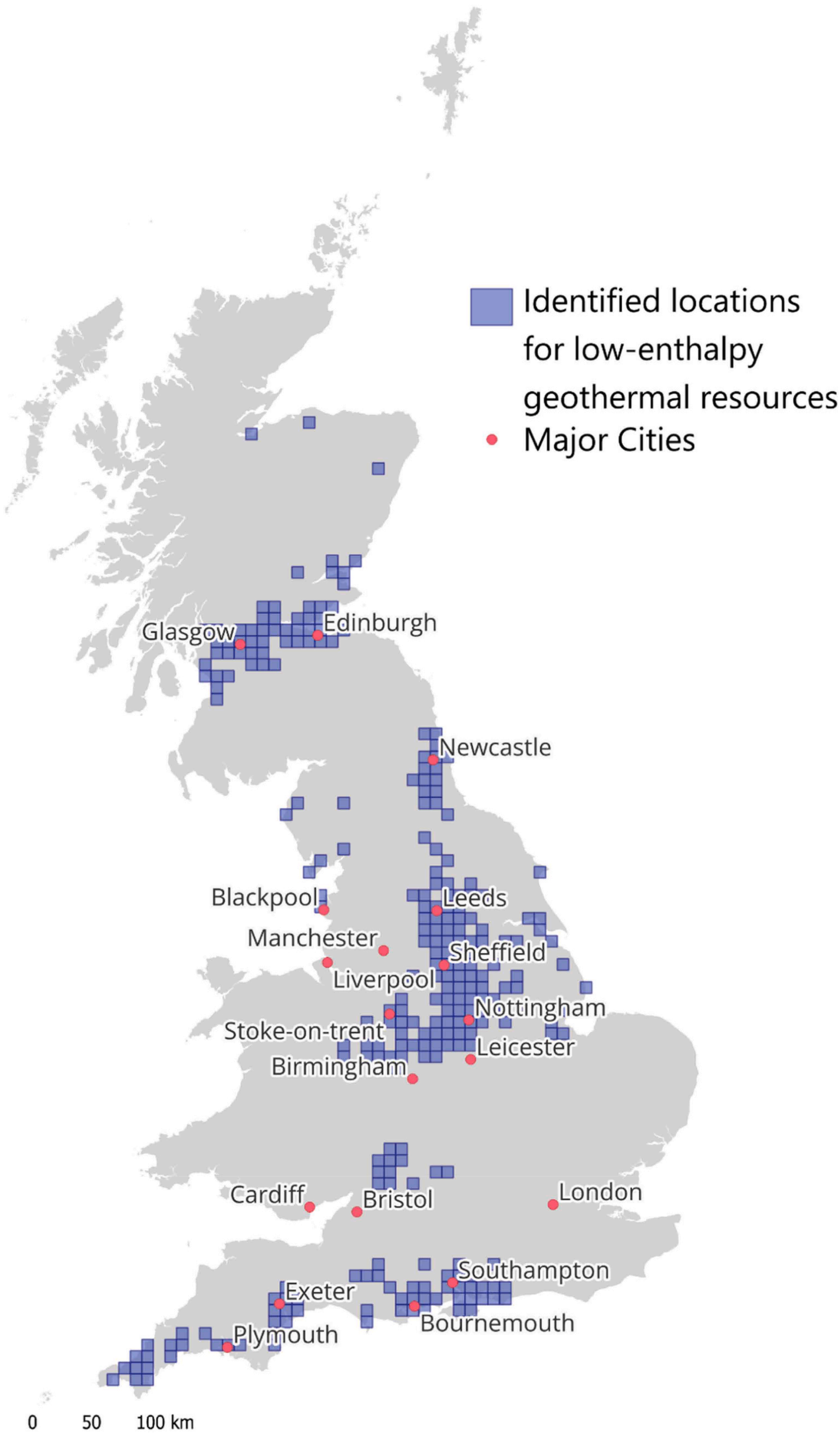


**Fig. 5.** Map of identified locations most suitable for deep geothermal heat networks.

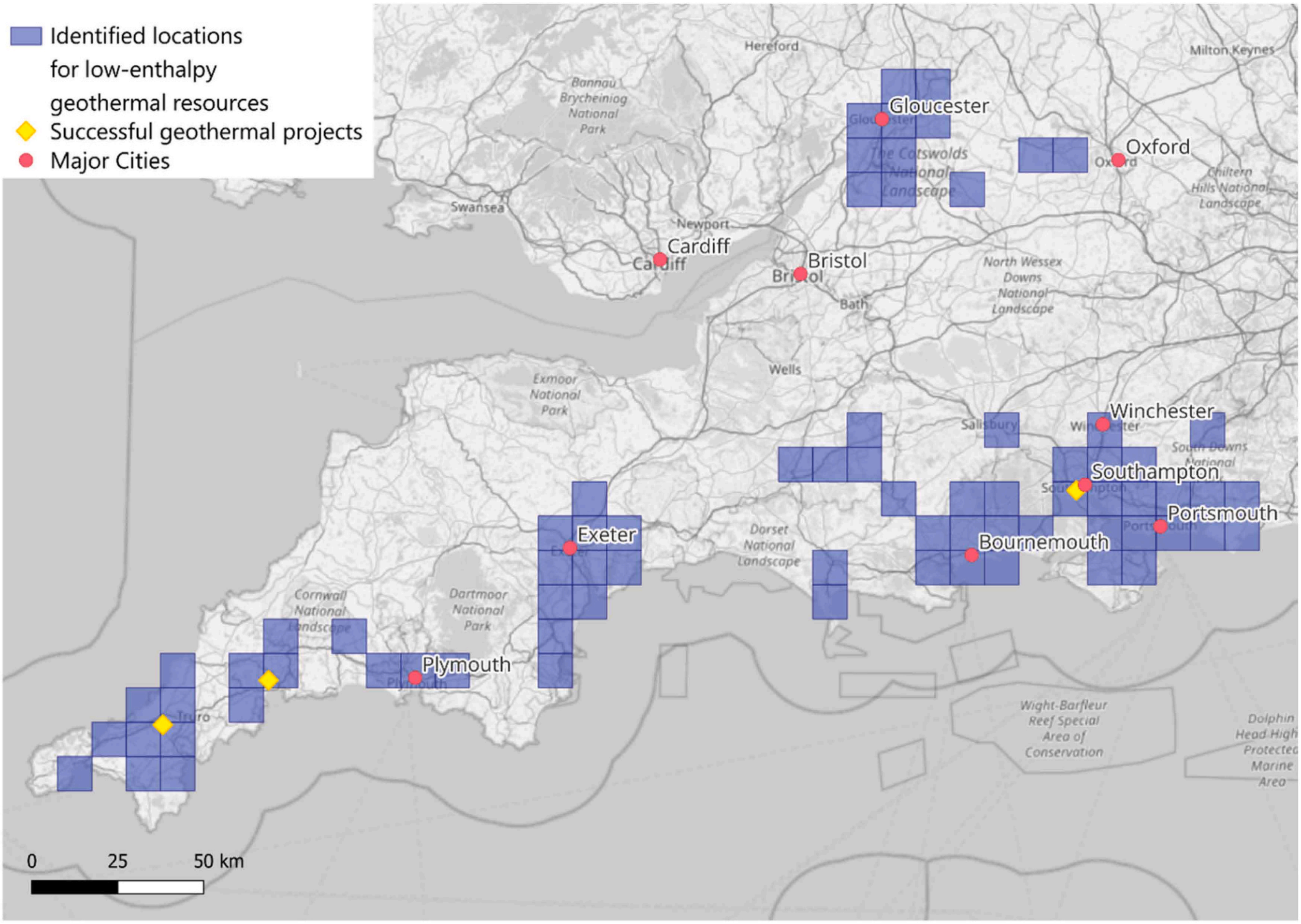


**Fig. 6.** Identified location most suitable for geothermal heat networks in Southwest England.

**Table 5**
Summary of grid boxes with highest heat flow values.

| Grid ID | Location | Demand % | Heat flow ($mW/m^2$) | Resource type |
|---|---|---|---|---|
| 2203 | Penzance | 6.1 | 106.9 | EGS |
| 2592 | Penryn | 10.0 | 105.8 | EGS |
| 2980 | St Blazey | 6.1 | 103.7 | EGS |
| 2591 | Truro | 8.1 | 103.7 | EGS |
| 2462 | Cambourne, Redruth | 13.8 | 103.6 | EGS |

(0.74 EJ), the geothermal resources meeting the criteria set for the analysis in this work could in theory meet demand in these areas for 270 years. Whilst the practical capacity is expected to be significantly less than the theoretical capacity, these findings indicate a technology that is being under-utilised in the low carbon energy transition.

This study serves as an early decision-making tool for stakeholders who are investigating locations for deep geothermal energy projects in Great Britain. However, it cannot be used to accurately predict the performance of a geothermal resource. Several limitations should be considered when interpreting the results of this study. The output is limited by the restricted scope of the selected data, which is deemed appropriate at national scale but introduces uncertainty when interpreting results at local scale. For example, the datasets did not consider parameters related to reservoir pore fluid volume or transmissibility, for which the data is somewhat sparse and more suited to analyses at local and regional scales. This means that the technical feasibility of a resource can only be suggested, not confirmed. This study does not consider regulatory requirements for deep geothermal projects. This includes permitting, licensing, and compliance with environmental regulations. The study does not consider the social and regulatory factors that impact the feasibility of a scheme and as a result, the precise location of a potential heat network within each grid box has not been included.

## 5. Conclusions

This work has presented a geospatial analysis of the potential for unconventional geothermal resources to supply heat networks in Great Britain. Existing resource assessments have focused on identifying and characterising the geothermal heat in place with less attention given to the heat demand itself. These preceding geospatial analyses linked the available heat to demand through collocation of geothermal resources with urban environments, providing a qualitative summary of practical potential. The present work builds upon previous findings by analysing the available resources alongside heat demand in an integrated and quantified manner on a 10 $km^2$ grid of the study area. A multi-criteria approach is adopted based on three types of map: (1) a geological map of suitable sedimentary aquifers and granite formations, (2) a heat flow map, and (3) a new demand map developed by considering a direct correlation between building volume and heat demand. The specific criteria applied to each grid box are a heat demand of at least 5% of that of the grid box with greatest heat demand, a heat flow of 50 $mW/m^2$ or more, and collocation with available geothermal resources. Maps (1) and (2) have been developed by collating three existing maps presented in the literature, including the Geothermal Map of Great Britain. In this

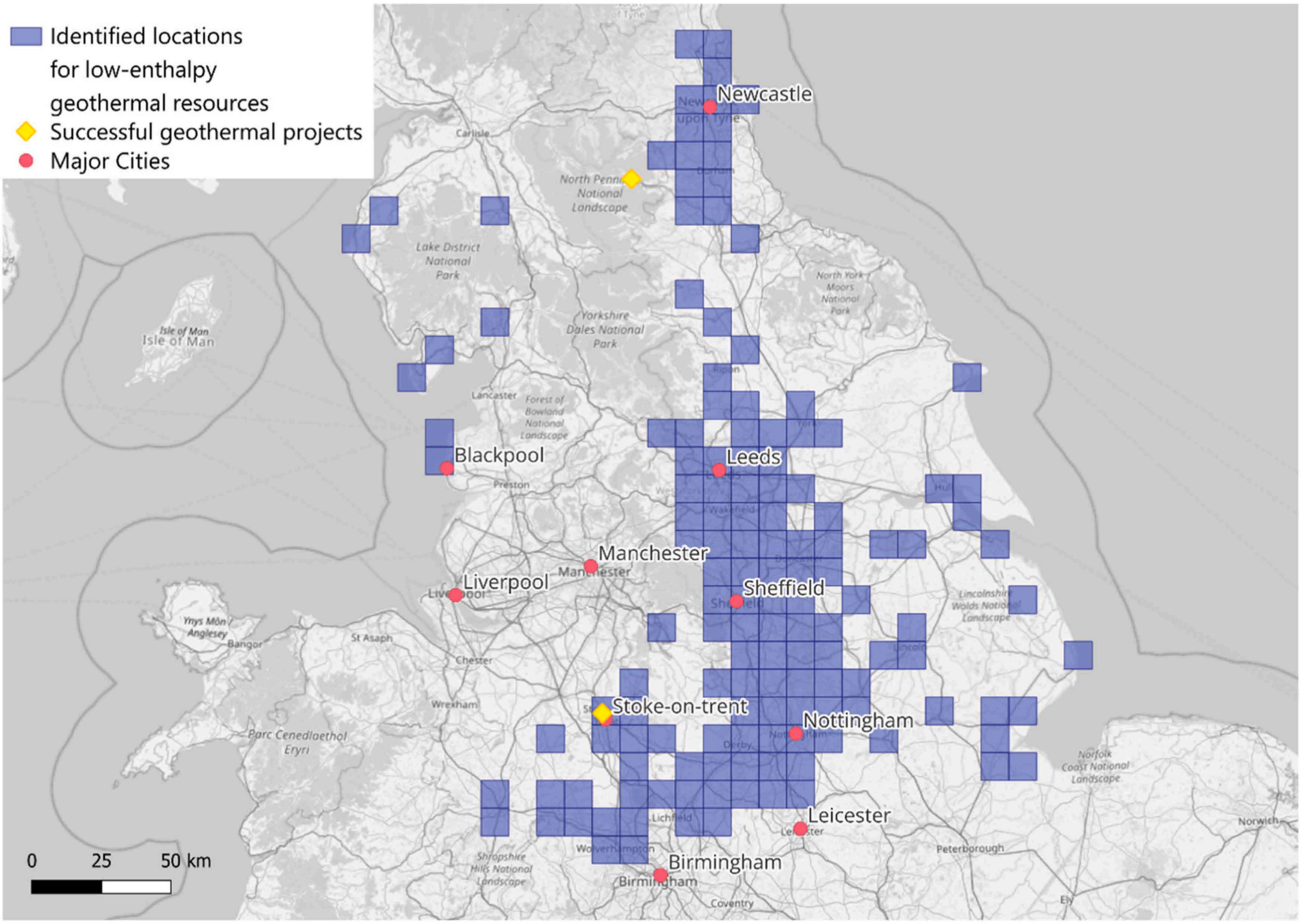


**Fig. 7.** Identified location most suitable for geothermal heat networks in the Midlands and Northern England.

manner, the present study avoids duplicating previous works that have extensively identified and characterised geothermal reservoirs in the study area. The principal novel contribution of this work is to analyse these maps alongside the new demand map to explore the practical potential in greater detail.

It has been determined that 9.8% of the Great Britain study area has deep geothermal energy supply potential aligned with sufficient demand for direct heating. Implementing geothermal heat networks in this 9.8% area could decarbonise up to 27% of Great Britain's overall heat demand. Although matched potential is expected to be considerably lower due to other social and techno-economic constraints not considered, the findings indicate that unconventional geothermal resources can make a significant contribution to increasing the market share of heat networks from 3% to 20% by 2050, which is a key goal on the pathway to net zero emissions in the buildings sector.

Of the identified potential, 83% is associated with sedimentary aquifers and 17% with granite formations. Grid boxes with most potential for geothermal heat networks are predominantly clustered in Southwest England, the Midlands, Northern England, and the Midland Valley of Scotland. These findings are consistent with previous inferences in the literature, but the present study has implemented an approach that explicitly quantifies heat demand for reduced uncertainty with improved spatial resolution. This is an important advance towards practical understanding of the potential of deep geothermal heat networks to contribute to the decarbonisation of heat, which remains a significant and unsolved issue for the UK.

Whilst this study complements existing literature by linking heat supply with demand, there are several limitations that should be considered when interpreting and applying the findings. Input datasets did not account for reservoir pore fluid volume or transmissibility, for which the data is somewhat sparse and more suited to analyses at local and regional scales. Whilst accounting for heat demand can be seen to implicitly account for an important aspect of the techno-economic case, a detailed techno-economic assessment was beyond the scope of this work. Furthermore, regulatory requirements were not considered. As a result, the technical feasibility of a resource has been suggested but not confirmed in this work, which is instead intended as an early decision-making tool for stakeholders to prioritise further site-specific investigation of deep geothermal heat networks in Great Britain.

## CRediT authorship contribution statement

**Juliet HOWES:** Writing – original draft, Validation, Methodology, Investigation, Formal analysis. **Lee James Hosking:** Writing – review & editing, Supervision, Methodology, Conceptualization.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The data underpinning this publication can be accessed from Brunel University London's data repository, Brunelfigshare here under a CCBY

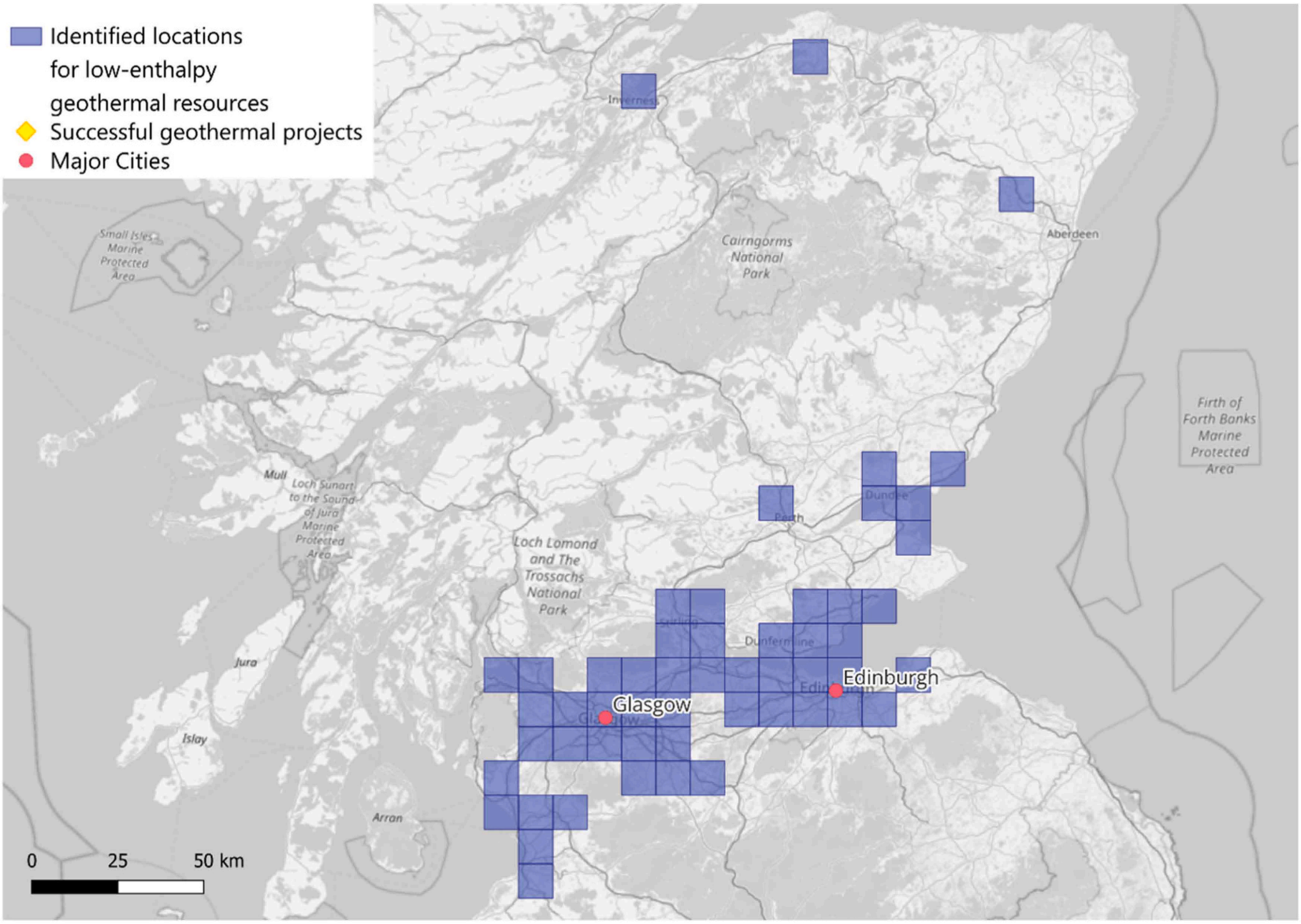


**Fig. 8.** Identified location most suitable for geothermal heat networks in Scotland.

**Table 6**
Summary of the top five options in terms of heat demand.

| Grid ID | Location | Demand % | Heat flow ($mW/m^2$) | Resource type |
|---|---|---|---|---|
| 5426 | Birmingham | 67.0 | 52.0 | HSA |
| 5937 | Sheffield | 63.2 | 68.6 | HSA |
| 5789 | Newcastle | 56.3 | 82.8 | HSA |
| 3569 | Glasgow | 55.3 | 56.2 | HSA |
| 6202 | Nottingham | 54.1 | 68.1 | HSA |

licence: 10.17633/rd.brunel.25965187.

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