Busby and Terrington *Geotherm Energy (2017) 5:7*
DOI 10.1186/s40517-017-0066-z

Geothermal Energy

RESEARCH Open Access

Assessment of the resource base for engineered geothermal systems in Great Britain

Jon Busby* and Ricky Terrington

*Correspondence:
jpbu@bgs.ac.uk
British Geological Survey,
Keyworth, Nottingham NG12
5GG, UK

Abstract

An assessment of the engineered geothermal system (EGS) resource base that might be available for the generation of electricity for Great Britain has been undertaken by adopting a globally self-consistent protocol that if universally adopted, would allow estimates of EGS made for different countries and regions to be comparable. Maximum estimated temperatures at depths of 5 and 7 km are greater than 200 and 300 °C respectively, a considerable increase over previous estimates. The total heat in place in the basement, to a depth of 9.5 km that is theoretically available for EGS is 357,197 EJ. If it were possible to develop just 2% of this resource, this would be equivalent to 1242 times the final UK energy consumption in 2015. The theoretical and technical potential power has been calculated from the available heat in place. The total technical potential power, to a depth of 6.5 km, is 222,393 MW_e and represents just 0.4% of the theoretical potential power. Current EGS exploitation is more likely to be restricted to a depths of around 4.5 km and reservoir temperatures greater than 175 °C. In which case technical potential power is mainly restricted to regions of high heat producing granites and represents a total technical potential power of 2280 MW_e. However, improvements in drilling technology are expected to enable economic drilling to depths of 7 km or greater that will enable EGS exploitation in all regions of Great Britain.

Keywords: EGS resource base, Great Britain, Heat in place, Theoretical potential power, Technical potential power

Background

Engineered or enhanced geothermal systems (EGS) have been promoted as a technology that exploits geothermal heat and power production from regions of the crust devoid of shallow high enthalpy reservoirs (also referred to as high-grade hydrothermal resources) (e.g., MIT 2006). The status of EGS development was reviewed by Breede et al. (2013) who reported on 14 EGS projects that were generating electricity and 8 that were still under development. EGS projects to date have been developed for power generation or combined heat and power, but the ECOGI project in northern Alsace, France is the first for heat only (Baujard et al. 2015). There is no single definition for EGS. MIT (2006) consider it as an 'engineered reservoir created to extract economical amounts of heat from low permeability and/or porosity geothermal resources and therefore includes all geothermal resources that are not in commercial production and require stimulation or enhancement'. Under this definition only high-grade hydrothermal resources are excluded as conduction dominated low permeability resources, geopressured, magma, low-grade unproductive hydrothermal resources and coproduced hot water from hydrocarbon production are all included. Rybach (2010) described an EGS 'as an extended fracture network, created and/or enlarged, to act as new fluid pathways and at the same time a heat exchanger, at depths where temperatures are high enough for power generation (150–200 °C)'. The Australian Geothermal Reporting Code Committee gives an even more general definition as 'a body of rock containing useful energy, the recoverability of which has been increased by artificial means such as fracturing' (AGRCC 2010). MIT (2006) and Blackwell et al. (2007) estimated the EGS resource base for the conterminous United States as the heat in place, tabulated by 1 km depth intervals, between 3.5 and 9.5 km depth. Temperature was calculated from the one dimensional heat conduction equation that included the contribution from the radioactive heat production of the upper crust. Limberger et al. (2014) adopted a slightly different approach for assessing the prospective EGS resource base for Europe, where vertical heat conduction was assumed, but the temperature distribution was solved by a 3-D finite difference method. They went further in also calculating the theoretical and technical potential power and the economic potential for EGS.

Given the range of EGS definitions, estimates of the prospective EGS resource base are likely to be diverse depending on the definition adopted. Beardsmore et al. (2010, 2011) proposed a protocol for estimating the theoretical and technical potential power for EGS that might be available for the generation of electricity, in a globally self-consistent manner. If universally adopted, then estimates of EGS made for different countries and regions would be comparable. The Beardsmore et al. (2010, 2011) protocol calculates both a theoretical and technical potential power as proposed by Rybach (2010). The theoretical potential is as an estimate of 'the physically usable energy supply over a certain time span in a given region. It is defined solely by the physical limits of use and thus marks the upper limit of the theoretically realisable energy supply contribution'. The technical potential is 'the fraction of the theoretical potential that can be used under the existing technical restrictions… structural and ecological restrictions as well as legal and regulatory allowances'. The principal difference between the Beardsmore et al. (2010, 2011) protocols is that the former includes both the basement and sedimentary sections for EGS assessment, whilst the latter only includes the basement. Inclusion of the sedimentary section is a matter for debate as sedimentary rocks with favourable porosity and permeability can be developed as hot sedimentary aquifer (HSA) resources.

This paper presents an evaluation of the prospective resource base for EGS power generation in Great Britain (GB) by applying the protocol of Beardsmore et al. (2010, 2011), hereafter referred to as the protocol. The EGS assessment presented here is for the basement only. The earliest assessment for Great Britain by Gale and Rollin (1986) calculated the heat stored in rocks between the 100 °C isotherm and a depth of 7 km that was referred to as the UK hot dry rock accessible resource base (HDR ARB). However, the assessment was not restricted to hot dry rocks, but included all strata including the deep sedimentary basins. The total UK HDR ARB was calculated to be 3.58×10^{10} or 3.26×10^{10} TJ for Great Britain only. No attempt was made to consider power potential. Two recent EGS assessments have produced divergent estimates for the United

Kingdom. SKM (2012) only considered the high heat producing granites from 3 regions to a depth of 5 km and estimated a total installed generation potential of 9.3 GW_e. Atkins (2013) carried out an assessment based on economic considerations and concluded that for the same high heat producing granites the current development potential was only 170 MW_e, which could tentatively rise to 1.0–1.5 GW_e by 2050.

The Beardsmore protocol

The protocol estimates the EGS potential to a depth of 10 km and is based on a simple 2-layer model comprising sedimentary rocks overlying basement. Heat transport is assumed to be by vertical conduction only. It is recommended that the region under investigation is split into a regular grid based on a geographic coordinate cell size of $5' \times 5'$ ($' =$ minute), which equates to different physical surface areas at different latitudes. A simplified workflow diagram of the protocol is shown in Fig. 1.

The first element is to model temperature at 1 km depth layers based on surface heat flow, mean surface temperature, the thermal conductivity structure of the 2-layer model and heat production within the sedimentary layer and basement. The average thermal conductivity of the sedimentary section (K_S) is the thickness-weighted, temperature-corrected harmonic mean of all the formations that make up the sedimentary section. Similarly, the average heat generation (A_S) is the thickness-weighted arithmetic mean of all the sedimentary formations. Where the exact sedimentary composition is unknown it is recommended to use constant values derived from published data compilations. Basement thermal conductivity (K_B) and heat production (A_B) must also be estimated and will largely be based on the assumption that the basement comprises a single lithology, unless there is mapping evidence to the contrary. There is a two-step procedure in the calculation of temperatures at depth. It is first necessary to calculate the temperature and heat flow at the sediment-basement interface. For the temperature calculation a distinction is made depending on whether the sediment thickness, S, is less than or greater than 4000 m, as follows,

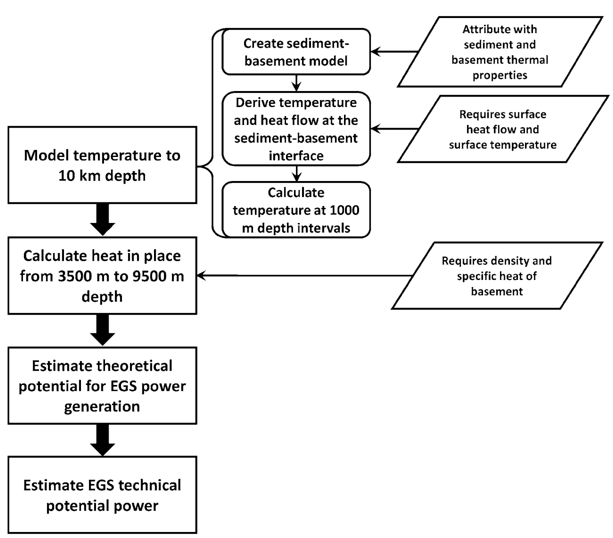

Fig. 1 Simplified workflow diagram of the Beardsmore protocol for estimating EGS potential

If $S < 4000$ m:

$$T_S = T_0 + \left[\frac{Q_0 S}{K_S}\right] - A_s\left[\frac{S^2}{2K_S}\right] \tag{1}$$

where T_S (°C) is the temperature at the sediment–basement interface, T_0 (°C) is the mean annual air temperature, Q_0 (W m^{-2}) is surface heat flow, K_S (W m^{-1} K^{-1}) is sediment thermal conductivity and A_S (W m^{-3}) is the sediment heat generation.

If $S > 4000$ m:

$$T_S = T_{4\ \mathrm{km}} + \left[\frac{(Q_0 - 4000A_S)(S - 4000)}{K_\mathrm{B}}\right] - A_s\left[\frac{(S-4000)^2}{2K_\mathrm{B}}\right] \tag{2}$$

where $T_{4\ \mathrm{km}}$ is the temperature at a depth of 4000 m from Eq. 1. It should be noted that the protocol assumes that the thermal conductivity of sediment deeper than 4000 m is the same as the basement, K_B (W m^{-1} K^{-1}). Heat flow at the sediment–basement interface is derived from,

$$Q_S = Q_0 - SA_S \tag{3}$$

where Q_S (W m^{-2}) is heat flow at the sediment–basement interface. The second step is to calculate temperatures at the mid-point of each 1000 m depth interval from 3000 m to the base of the model, i.e. at depths X (m) equal to 3500, 4500, 5500, 6500, 7500, 8500 and 9500 m.

$$T_X = T_S + \left[\frac{Q_S(X - S)}{K_\mathrm{B}}\right] - A_\mathrm{B}\left[\frac{(X-S)^2}{2K_\mathrm{B}}\right] \tag{4}$$

where T_X (°C) is the temperature at depth X.

The second element of the protocol is to estimate the available heat in place at the mid-point of each of the depth slices from 3500 to 9500 m. To follow the protocol, EGS potential is only based on heat contained within the basement, hence excluding intervals of sediment. The available heat H in EJ (exajoule $= 10^{18}$ J) for each basement cell is given by,

$$H = \rho\, C_\mathrm{P}\, V_\mathrm{C}(T_X - T_\mathrm{R}) \times 10^{-18} \tag{5}$$

where ρ (kg m^{-3}) is the density and C_P (J kg^{-1} K^{-1}) is the specific heat of the basement cell, V_C (m^3) is the volume of the cell, T_X (°C) is the temperature at depth X and $T_\mathrm{R} = T_0 + 80$ °C where T_0 (°C) is the mean annual air temperature. T_R is the base temperature to which the crust can theoretically be reduced by abstracting geothermal heat. The assumption adopted by the protocol that the base temperature is 80 °C above mean annual air temperature differs from previous methodologies (MIT 2006; Blackwell et al. 2007) where T_R was equal to the mean ambient air temperature.

The third element of the protocol is to derive the theoretical and technical potential power. Theoretical potential power generation is derived assuming that all heat, H, above the base temperature, T_R, is theoretically recoverable at all locations, that the life span of power generation is 30 years (9.46×10^8 s) and the cycle thermal efficiency (the proportion of heat delivered to a power plant that is converted to electricity), η_{th}, is a function of inlet temperature. Theoretical potential power generation P (MW_e) for each basement cell is given by,

$$P = \frac{\eta_{\text{th}} H \times 10^{12}}{9.46 \times 10^{8}} \tag{6}$$

Cycle thermal efficiencies are plant dependent and are likely to improve with time due to developments in power plant technologies. The protocol recommends applying a set of average cycle thermal efficiencies from MIT (2006) for a range of inlet fluid temperatures from 150 to 350 °C, described by,

$$\eta_{\text{th}} = 0.00052 T_X + 0.032 \tag{7}$$

Theoretical potential power generation is calculated for each basement cell for the 1 km depth slices between 3500 and 9500 m. The technical potential power is that part of the theoretical potential that can be extracted after consideration of currently 'insurmountable' technical limitations (Rybach 2010). The protocol recommends consideration of four technical limitations comprising land access, accessible depth, recoverability factor and temperature drawdown. Limitations on land access will vary between regions, but will include conservation areas, densely populated areas, large lakes etc. For each grid cell, the proportion of land that is available, R_{av}, is assigned a value between 0 and 1. The protocol recommends limiting the accessible depth to 6500 m as this is the practical limitation to EGS development imposed by current drilling technology. Recoverability factor, R, is an estimate of the proportion of thermal energy that can be recovered from a fracture dominated geothermal system. Temperature drawdown allows for the reduction of geothermal fluid temperatures with time as cool fluid is reinjected into the reservoir. The protocol introduces a temperature drawdown recoverability factor, R_{TD} that allows for a maximum allowable temperature drawdown of 10 °C. It is defined as,

$$R_{\text{TD}} = \frac{10}{(T_X - T_{\text{R}})} \tag{8}$$

Technical potential power, P_{T} (MW_e), is given by

$$P_{\text{T}} = P R_{\text{av}} R R_{\text{TD}} \tag{9}$$

and is calculated for depth intervals between 3500 and 6500 m, the sum of which gives the total technical potential power for each basement grid cell.

The final elements of the protocol are some estimates of the level of confidence in the estimates and the presentation of the results using common visualisation and data architecture.

Application of the protocol to Great Britain

Model and output layers were defined as a series of 1 × 1 km grids based on the British National Grid (BNG). This differs from the protocol where the recommended cell size is 5′ × 5′. For Great Britain this geographic cell has an approximate easting x northing dimension of 5 × 9 km, but this varies with latitude. The adoption of a finer grid prevents the areal error in the location of estimated EGS resources which can occur with a coarse grid where the resource is spread across a large dimension grid cell. In the sections below a description is given of the selection of properties for the model and these are summarised in Table 1.

Modelled temperatures at depth

The first step was to create the sediment–basement model from a grid of sediment thickness (depth to basement). The protocol does not give a definition for basement, but it is usually interpreted as the rock underlying the oldest stratified rocks. Metasedimentary rocks are often considered as basement, but there could be instances where low-grade metasediments are classed as sedimentary rocks. There is also a practical consideration in estimating the depth to basement because in Great Britain the depth to base Lower Palaeozoic is rarely known. Hence, the depth to basement has been defined as the depth to base Devonian, or younger in the absence of older rocks, with the exception of outcropping or intruded granites. This definition is inevitably a compromise as there will be some Lower Palaeozoic rocks with sedimentary affiliations (e.g. mid and north Wales) and some tectonised and metamorphosed Carboniferous and Devonian rocks (e.g. the Variscides of Southern GB). The depth to basement rocks surface was constructed from a series of surfaces exported from the BGS (British Geological Survey) LithoFrame 1:1 M model (http://www.bgs.ac.uk/services/3Dgeology/lithoframe.html). The LithoFrame 1:1 M surface model was constructed in Paradigm® GOCAD® in 2004 and was largely based on Whittaker (1985) and seismic data where data was limited in the deeper subsurface. The surfaces were modelled at a 1 km mesh spacing and represent the major stratigraphic divisions in the UK. They include the following for the calculation of the sediment thickness:

Table 1 Summary of the physical properties adopted in the sediment–basement model

	Min	Max	Mean	
Sediment thermal conductivity (W m^{-1} K^{-1})				
Palaeogene–Permian	2.04	3.22	2.37	
Carboniferous–Devonian	2.25	2.98	2.68	
Sediment heat production (μ Wm^{-3})	0.45	1.86	1.17	
Basement thermal conductivity (W m^{-1} K^{-1})				
Non-granitic	2.03	4.43	3.06	
Granitic	2.88	3.65	3.3	
Basement heat production (μ Wm^{-3})				
Non-granitic	0.3	3.0	1.46	
Granitic			5 km depth	10 km depth
Southwest England			4.6	4.6
Northern England			3.06	2.46
Southern Uplands			1.87	1.5
East Grampians			2.98	1.9
Other Scottish			1.34	1.08
Basement density (kg m^{-3})	2270	3270	2800	
Basement specific heat (J kg^{-1} K^{-1})	540	1347	887	

The methodology for the adoption of these properties across the grids of the model are described in the text. It should be noted that the thermal conductivities in the table are at laboratory temperatures and are corrected for temperatures at depth when attributed to the model

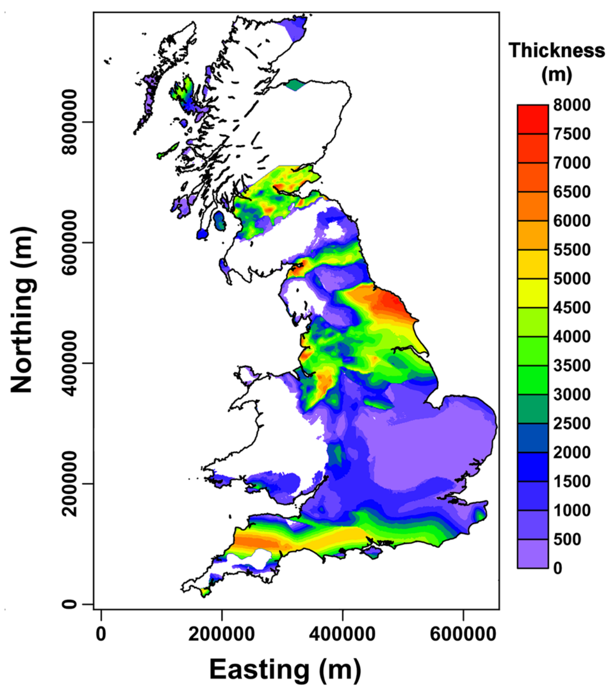

Fig. 2 Sediment thickness model to base Devonian, which also defines the depth to basement, derived from the BGS Lithoframe 1:1M model. Areas in white are exposed basement

- Base Palaeogene
- Base Cretaceous
- Base Jurassic
- Base Triassic
- Base Permian
- Base Carboniferous
- Base Devonian.

To calculate the sediment thickness, the surfaces were imported into a geographic information system (ArcGIS® software by Esri) as gridded data at 1 km spacing. Using the raster calculator, a conditional statement was used to generate a new grid which showed the maximum depth of the combined surfaces considered to be above the basement, therefore the new grid generated represented the base of sedimentary rocks or top of the basement rocks, but not including areas where basement rocks were at surface/outcrop. To calculate the sediment thickness, the raster calculator was used to subtract the base sediment surface from the Digital Terrain Model (OS Open 50—which was recalculated to a 1 km grid spacing for this study). The sediment thickness map is shown in Fig. 2.

The sediment thickness grid requires single values of thermal conductivity and heat generation for each grid cell to characterise the thermal properties for the full depth of the sediment section. Ideally, the average vertical thermal conductivity is the temperature corrected, thickness weighted harmonic mean of the formation thermal conductivities that comprise the sedimentary section at each grid cell. As thermal conductivity grids for each of the stratigraphic surfaces do not exist a simpler procedure has been adopted. For the purposes of thermal conductivity attribution a model interface has been inserted within the sedimentary section at the base Permian or younger. This therefore splits the sedimentary section, where the strata exist, into Palaeogene–Permian and Carboniferous–Devonian. Representative, vertical sections were then selected across Great Britain from the BGS GB3D national geological model (Mathers et al. 2014), which maps all the principal geological formations as a fence diagram of the bedrock geology. For each vertical section, the thickness weighted harmonic mean thermal conductivity has been calculated for the Palaeogene–Permian and Carboniferous–Devonian sequences with thermal conductivities of individual formations taken from Rollin (2002). The vertical sections were selected from sedimentary basin and off-basin regions and comprised 8 Palaeogene–Permian and 11 Carboniferous–Devonian vertical sections. The mean of the harmonic mean thermal conductivities was 2.37 ± 0.5 W m^{-1} K^{-1} for the Palaeogene–Permian and 2.68 ± 0.24 W m^{-1} K^{-1} for the Carboniferous–Devonian. These two thermal conductivities are at laboratory temperature and have been corrected for temperature at depth across the grid using the algorithm of Vosteen and Schellschmidt (2003). The depth at which to calculate the temperature was taken at the mid-depth Palaeogene–Permian and/or Carboniferous–Devonian thickness and the temperature was calculated assuming a geothermal gradient of 28 °C km^{-1} (Busby et al. 2011). The final, single value, thermal conductivity assigned to each grid cell of the sedimentary section was the thickness weighted harmonic mean of the Palaeogene–Permian and/or Carboniferous–Devonian temperature corrected thermal conductivities. The range of thermal conductivity across the grid (K_S) was 2.18–2.77 W m^{-1} K^{-1}.

Heat generation of sedimentary rocks is generally low. Rollin (2002) lists heat generation for the principal British geological formations, the mean of which for sedimentary rocks (A_S; to base Devonian) was 1.17 μ Wm^{-3} and this single value was adopted across the sediment thickness grid.

The basement layer of the model also requires thermal properties. From Rollin (2002), the thermal conductivities of 63 lithostratigraphies that comprise basement rocks in Great Britain (excluding granites) were averaged to give a mean value of 3.06 W m^{-1} K^{-1}. The temperature corrected value to a depth of 5 km (K_B), the mid-depth of the model, using the algorithm of Vosteen and Schellschmidt (2003), was 2.54 W m^{-1} K^{-1} and this was applied as a single value across the basement layer in non-granitic regions. For granitic regions (see Fig. 3) a basement surface thermal conductivity of 3.3 W m^{-1} K^{-1} (Downing and Gray 1986a) was assigned, which was temperature corrected for depth to 2.71 W m^{-1} K^{-1}.

Heat generation within the basement layer is larger and more variable than the sediment layer, especially in regions of heat producing granitic rocks. For non-granitic areas, an average heat production for basement rocks of 1.46 μ Wm^{-3} was calculated from Rollin (2002). Five regions of granites are known across Great Britain and are shown in Fig. 3. These were assigned surface heat production values (A_0) as follows; Southwest England, 4.6 μ Wm^{-3} (Lee et al. 1987); northern England, 4.1 μ Wm^{-3} (Lee et al. 1987); Southern Uplands, 2.5 μ Wm^{-3} (Downing and Gray 1986a); East Grampians, 6.0 μ Wm^{-3} (Downing and Gray 1986a); other Scottish granites, 1.8 μ Wm^{-3} (Downing and Gray 1986a). Lee et al. (1987) indicate that the heat production is most likely to be constant to a depth of 10 km in southwest England, but in other areas it decreases

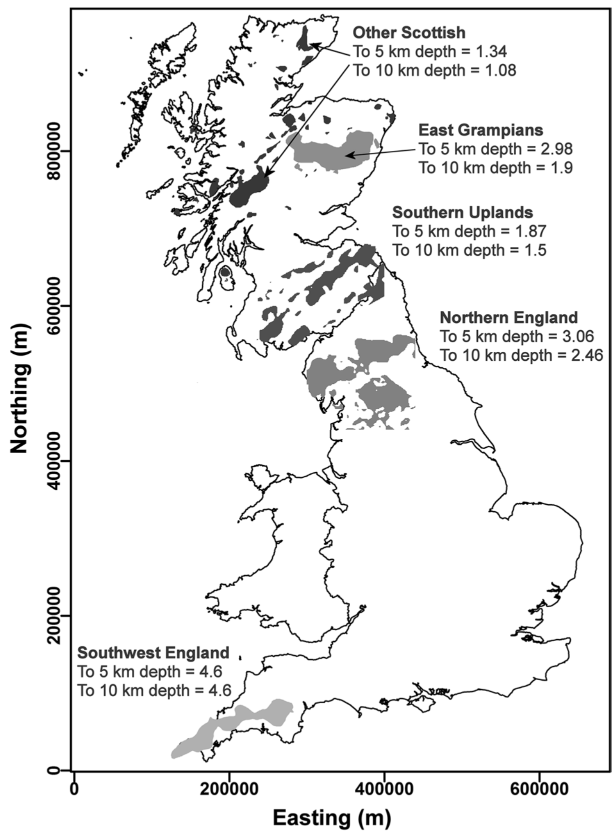

Fig. 3 Locations in Great Britain with significant quantities of heat producing granites within the upper crust. Quantitative figures of average heat production in, μWm^{-3}, are shown for depths to 5 and 10 km respectively

exponentially with depth. It has therefore been assumed that, except in southwest England, heat production decreases with depth according to;

$$A_z = A_0 \mathrm{e}^{\left(\frac{-z}{D}\right)} \tag{10}$$

where A_z (μ Wm^{-3}) is the heat production at depth z and D is the range of depth over which the heat production decreases to 1/e (0.37) of its surface value. For the high heat producing Scottish granites of the East Grampians, D has been assigned a value of 4 km (Busby et al. 2015) and for the other three regions of granite, a value of 10 km (Westaway and Bridgland 2014). With these parameters the average heat production value was calculated for each of the granitic areas to depths of 5 and 10 km and these are shown in Fig. 3. Hence, these two grids of heat production values account for the change of heat production with depth with two values (split at a depth of 5 km) rather than a single value for the whole crustal section. These were used for temperature calculations to 5 km and 5–10 km depth respectively.

The final two elements required for the modelling of temperatures at depth are the surface heat flow and the mean surface temperature. The heat flow map of the UK has been presented and discussed by Lee et al. (1987), Downing and Gray (1986a, b), Rollin (1995), Barker et al. (2000) and Busby et al. (2009). It comprises 212 heat flow measurements augmented by 504 heat flow estimates. There is a fairly uniform background field with areas of increased heat flow associated with the radiogenic granites in southwestern England and the buried granites of northern England. Values are also above the regional background over the batholith in the East Grampians of Scotland. These data were not corrected for the effects of palaeoclimate and topography, except over the southwestern England granites where a correction for recent palaeoclimate changes was applied (Wheildon et al. 1981). Westaway and Younger (2013) have indicated that the lack of consistent palaeoclimate corrections, has led to an under estimation of UK heat flow and, therefore, an under estimation of geothermal resources at depth. Since surface heat flow is a critical parameter in the estimation of EGS potential, a crude regional correction scheme for palaeoclimate has been applied. It is based on published palaeoclimate and topographic heat flow corrections at six borehole sites across Great Britain (Westaway and Younger 2013), over the East Grampians batholith in eastern Scotland (Busby et al. 2015) and over the southwestern England granites (Beamish and Busby 2016). This has resulted in a positive correction of 16 mWm^{-2} to regions north of the approximate southern extent of the Devensian ice at the last glacial maximum and 20 mWm^{-2} south of the ice extent, where the extent of the Devensian ice was taken from Bowen et al. (2002). The exception is that a correction of only 9 mWm^{-2} was applied across southwestern England due to the partial correction applied for recent palaeoclimate changes. The correction of 20 mWm^{-2} for southern Britain is less than that quoted by Westaway and Younger (2013), of 27 mWm^{-2}. This arises since the average palaeoclimate correction over the southwestern England granites of 24 mWm^{-2} (Beamish and Busby 2016) has been reduced to correct for the lower average thermal conductivity of near surface upper crustal rocks across southern Britain of 2.75 $W\ m^{-1}\ K^{-1}$, (Clauser 2006) compared to 3.3 $W\ m^{-1}\ K^{-1}$ for granite. The heat flow map is shown in Fig. 4.

Mean surface temperature has been taken as the mean annual air temperature and is based on UK meteorological office annual long-term average data, as described in Busby et al. (2009).

These gridded parameters have been inserted into Eqs. (1) and (2) to derive the temperature at the sediment–basement interface and into Eq. (3) for an estimate of heat flow at the sediment–basement interface. Equation (4) has then been applied to calculate temperatures at 1000 m depth intervals between 3500 and 9500 m. It should be noted that the basement heat production, A_B, was the heat production to 5 km depth for temperature depth slices to 5000 m and the heat production to 10 km depth for deeper temperature depth slices. For comparison with previous publications, temperatures have also been derived for depth intervals of 5000 and 7000 m and these are shown in Fig. 5.

Estimation of available heat

Estimates of available heat were made with Eq. (5). As the composition of the British basement to a depth of 10,000 m is largely unknown, single values of density and specific heat were estimated. These were taken as the mean of the 40 densities and specific heats for metamorphic and intrusive rocks listed by Waples and Waples (2004), which resulted in an estimated basement density of 2800 $kg\ m^{-3}$ and basement specific heat of 887 $J\ kg^{-1}\ K^{-1}$. Note that T_R, the base temperature, is the temperature to which the crust can theoretically be reduced as a result of geothermal exploitation and, in accordance with the protocol, was taken as 80 °C above mean annual surface temperature at each

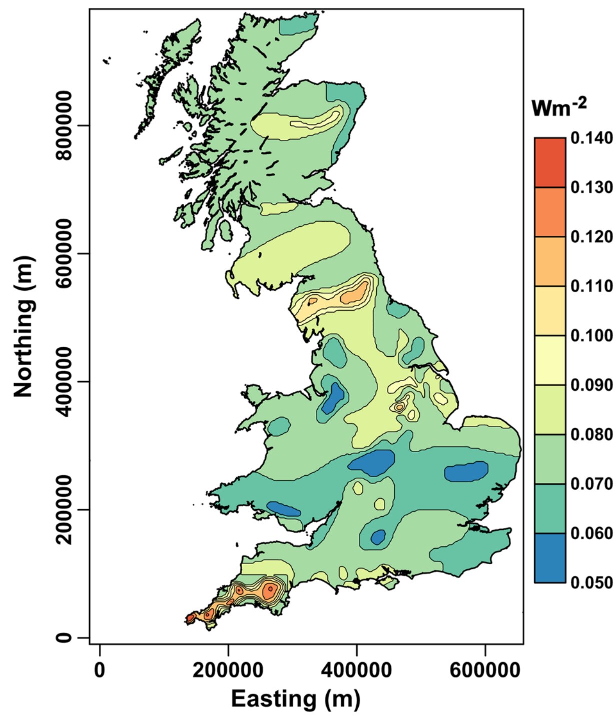

Fig. 4 Surface heat flow map for Great Britain that includes a first pass correction for the effects of palaeoclimate

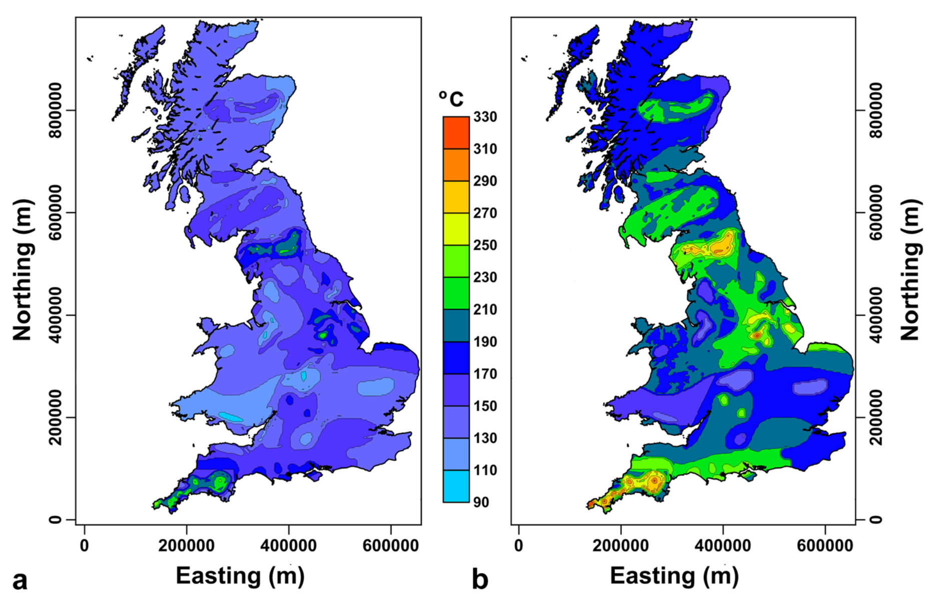

Fig. 5 Modelled temperatures at depths of **a** 5 km and **b** 7 km

location. It is possible for H to be negative if T_X is less than T_R, in which case H was set to zero. Tabulations of available heat by depth slice and temperature range are shown in Table 2.

Table 2 Available heat or heat in place, within the basement for the depth range 3.5–9.5 km

Depth slice (km)	Heat content (EJ) tabulated by temperature at depth						
	150 C	200 °C	250 °C	300 °C	350 °C	400 °C	450 °C
3.5	1424	0	0	0	0	0	0
4.5	17,616	1335	0	0	0	0	0
5.5	29,526	7856	713	0	0	0	0
6.5	10,990	38,112	4257	404	0	0	0
7.5	3750	44,936	16,463	2760	214	0	0
8.5	816	28,581	43,598	7112	1636	42	0
9.5	75	6848	61,542	21,736	4038	813	6

Heat contents, in EJ, are binned as ±25 °C around the central temperature, i.e. heat contents greater than or equal to 175 °C and less than 225 °C are binned as 200 °C. The available heat in place for Great Britain is 357,197 EJ

Derivation of theoretical and technical potential power

Theoretical potential power generation was calculated from the heat in place estimates for each 1 km^3 basement cell for the 1 km depth intervals between 3500 and 9500 m by application of Eqs. (6) and (7).

Technical potential power requires consideration of the four technical limitations comprising land access, accessible depth, recoverability factor and temperature drawdown. Land access has been estimated from the UK land cover map (Morton et al. 2011) which maps UK land cover to one of 23 classes at a parcel-based resolution of 25 m. This has been resampled to 50 m parcels resulting in 400 per 1 km^2 of the theoretical potential power grids. The proportion of each 1 km^2 grid cell that is available for EGS development, R_{av}, was calculated assuming that seven of the 23 classes are not suitable, where these were classified as offshore, bog (but not Fen marsh and swamp), montane habitats, salt water bodies, freshwater bodies, urban areas and suburban areas. Accessible depth was limited to the top 6500 m and recoverability factor, R, was assigned a mean value of 0.14 as recommended by the protocol. Temperature drawdown was calculated from Eq. (8) and technical potential power (MW_e) from Eq. (9). Tabulations of technical potential power by British region (see Fig 6), depth slice and temperature range are shown in Table 3.

Discussion

The estimate of EGS potential for Great Britain reported here has followed the protocol of Beardsmore et al. (2010, 2011). It is not possible to provide quantitative estimates of accuracy as much of the analysis is reliant on properties of the basement at depth. Data for the basement is sparse and therefore data gaps have been estimated from the best available general compilations. As such the estimate gives a general guide to EGS potential that can be compared to similar estimates from other countries and regions and shows the regional variability of EGS potential within Great Britain. The estimate should not be relied on to inform commercial investment decisions.

The final element of the protocol is to present the results using common visualisation and data architecture and the protocol recommends using Keyhole Markup Language (KML) that is suitable for upload to Google Earth. This has not been done here as there has been a debate as to whether dissemination of the results should be tied to a specific

Table 3 Tabulation of technical potential power by British region, depth slice and temperature range

	Scotland	NE England	NW England	York & Humb	East Mids	West Mids	Wales	E England	London	SE England	SW England
3.5 km depth Temp °C											
150	0	502	813	57	731	27	0	221	0	106	1413
200	0	0	0	0	0	0	0	0	0	0	0
250	0	0	0	0	0	0	0	0	0	0	0
300	0	0	0	0	0	0	0	0	0	0	0
4.5 km depth Temp °C											
150	18,334	1802	2898	3053	4322	2595	3822	2105	185	3620	4716
200	0	436	265	77	213	0	0	0	0	0	1289
250	0	0	0	0	0	0	0	0	0	0	0
300	0	0	0	0	0	0	0	0	0	0	0
5.5 km depth Temp °C											
150	23,158	1962	2722	2692	3557	3761	7398	6085	210	6484	5746
200	1738	878	1758	1998	2637	449	0	437	0	576	2698
250	0	77	21	0	76	0	0	0	0	0	804
300	0	0	0	0	0	0	0	0	0	0	0
6.5 km depth Temp °C											
150	4204	262	986	270	1282	2081	3573	5180	0	3482	958
200	23,767	2438	3361	5421	5103	3127	4803	2623	234	4240	7269
250	1	789	1154	247	617	7	0	0	0	165	2733
300	0	57	14	0	51	0	0	0	0	0	371
Total	71,202	9203	13,992	13,815	18,589	12,047	19,596	16,651	629	18,673	27,997

British regions are shown in Figure 6. Power contents, in MW_e, are binned as $\pm$ 25 °C around the central temperature, i.e. power contents greater than or equal to 175 °C and less than 225 °C are binned as 200 °C. The technical potential power for Great Britain is 222,393 MW_e

Fig. 6 Regions of Great Britain (Office for National Statistics Open Geography Portal:https://data.gov.uk/dataset/regionsdecember-2014-generalised-clipped-boundaries-in-great-britain1/resource/ab19204b-4b88-4f12-ab71-b15242b5ac83)

software package (C Bromley pers. Comm.), but publication of the results with KML or another software could be done in the future.

Temperature maps at depths of 5 and 7 km are shown in Fig. 5. At 5 km depth the minimum temperatures of around 100 °C occur in South Wales, whilst maximums of over 200 °C are associated with the Southwest England granites (see Fig. 3 for the location). At 7 km depth the minimum and maximum temperatures at the same locations are around 130 and 300 °C respectively. Rybach (2010), in his definition of EGS, quoted a minimum temperature range for power generation of 150–200 °C. At 5 km depth, the percentage area of GB crust at temperatures greater than or equal to 150 °C is 36% and greater than or equal to 200 °C is 1%. At 7 km depth, these percentages increase to 98 and 40% respectively. Downing and Gray (1986a; and reproduced in Barker et al. 2000) published a temperature map at 7 km depth. In general their temperatures are less than those estimated here. Their maximum temperature of ~260 °C is associated with the Southwest England granites and they estimated temperatures of 200–220 °C for the Northern England granites. The largest difference is associated with the East Grampians granites where Downing and Gray (1986a) predicted temperatures of only 140 °C, compared to 225 °C here. Temperatures at depth are dependent on the surface heat flow and since one dimensional, vertical, heat conduction has been assumed the pattern of temperature distribution at depth reflects that of surface heat flow. It is possible that some heat flow measurements may contain a component of convective heat transport. Bullard and Niblett (1951) suggested that the heat flow anomaly in the East Midlands (see Fig. 4) was due to convective water flow up a Carboniferous anticline, in which case it would not raise temperatures in the basement. However, there is evidence for Caledonian granitic intrusions within the crust of the East Midlands (Cornwall and Walker 1989) and so a conductive heat flow component cannot be ruled out.

Table 2 tabulates the heat in place, in exajoules (EJ) to a depth of 9.5 km, which is the heat in the basement that is theoretically available for EGS; a total of 357197 EJ. It is sometimes referred to as the geothermal resource base (e.g. Blackwell et al. 2007). If it were possible to develop just 2% of this resource (7144 EJ), this would be equivalent to 1242 times the final UK energy consumption in 2015. Gale and Rollin (1986) calculated the GB Hot Dry Rock Accessible Resource Base (HDR ARB) to a depth of 7 km as 3.26×10^{10} TJ. The heat in place to depth of 7.5 km calculated here is 18.04×10^{10} TJ, a 5.5-fold increase over the previous estimate. Heat in place estimates have also been made for direct use geothermal in Great Britain based on the deep Mesozoic basins and range from $198–293 \times 10^{6}$ TJ (Busby 2014), indicating that the geothermal resource base for EGS is around 700 times that for direct use. In reality this ratio will be less as there is some direct use geothermal potential within the Carboniferous and Devonian sedimentary basins (Busby 2014), but this is difficult to quantify due to a lack of deep permeability data for the upper Palaeozoic.

The total technical potential power that could be exploited by EGS technology is 222,393 MW_e (see Table 3). This represents just 0.4% of the theoretical potential power. It is a much higher estimate than those of SKM (2012) or Atkins (2013), although these were restricted to only 3 regions of high heat producing granites. All GB regions have technical potential, although London is the smallest and Scotland is the largest. Figure 7 shows the technical potential power density in MW_e km^{-2} across Great Britain for the depth range 3.5–6.5 km. The regions of high heat producing granites in southwest England and northern England are the most prospective, but other prospective regions are also evident in the East Midlands, southern and eastern Scotland. Although the protocol calculates technical potential power to a depth of 6.5 km, current geothermal exploration in Great Britain is more likely to be restricted to a depth of around 5.0 km and temperatures of around 200 °C. In which case technical potential is restricted to North East England, North West England, Yorkshire and The Humber, the East Midlands and South West England and represents a total technical potential power of 2280 MW_e.

Conclusions

The protocol of Beardsmore et al. (2010, 2011) has been applied to estimate the EGS potential available for power generation in Great Britain. At a depth of 7 km the percentage area of GB crust at temperatures greater than or equal to 150 °C is 98% and the heat in place within the basement to a depth of 9.5 km is 357,197 exajoules. Within current, insurmountable, technical limitations the technical potential power that could be utilised by EGS technology to a depth of 6.5 km is 222,393 MW_e. Current proposals for EGS systems in the UK, as known to the authors, quote depths of up to 4.5 km and temperatures of 190 °C. The technical potential power reduces to 2280 MW_e if exploitation is limited to depths of around 4.5 km and reservoir temperatures greater than 175 °C. The EGS potential assessment has been restricted to the basement, defined here as rock

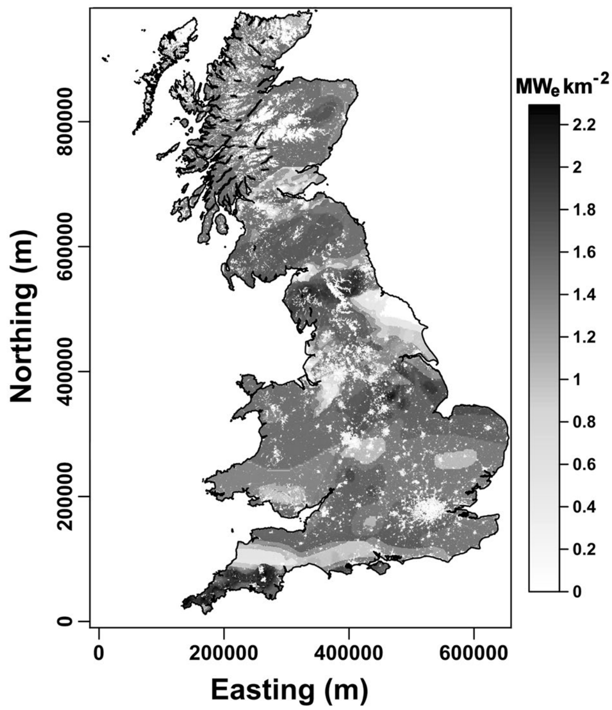

Fig. 7 Technical potential power density across Great Britain for the depth range 3.5-6.5 km. Areas with zero potential are mainly excluded as a result of land cover comprising urban settings and mountains

units beneath the base Devonian and outcropping or intruded granites. EGS reservoirs can also be exploited within the deep sedimentary section where stimulation could be by hydraulic fracturing or acidification (e.g. Breede et al. 2013; Knapek and Kittle 2007; Zimmermann et al. 2009). The sedimentary section in this study extends to depths in excess of 7 km (see Fig. 2) and so has EGS potential. This has not been considered here as the purpose of adhering to the protocol is that EGS estimates from different countries and regions can be compared.

Proposals to develop EGS within Great Britain have been restricted to the high heat producing granites of Southwest England, Northern England and the East Grampians (Downing and Gray 1986a; Busby 2010; Younger et al. 2012). The results presented here have shown that at depths of 4–5 km and temperatures in excess of 180 °C, the majority of the EGS potential is restricted to these granites. Breede et al. (2013) report that of 31 EGS projects worldwide, the deepest well drilled was 5093 m at Soultz-sous-Forêts in France and the average well depth was 3046 m. Drilling is the largest cost component of an EGS project (MIT 2006) and Lukawski et al. (2014) report that significant improvements in geothermal drilling technology over the last 35 years has reduced the rate at which well costs increase with depth. Continued improvements will allow economic drilling to 7 km depth which will enable EGS exploitation in all regions of Great Britain.

Authors' contributions

JB undertook the analysis and calculations to determine the heat in place, theoretical and technical potential power of the GB EGS resource base. RT generated the sedimentary cover over basement model. Both authors read and approved the final manuscript.

Acknowledgements
Our thanks go to Melinda Lewis for an internal review of the manuscript. The models and maps contain Ordnance Survey data © Crown copyright and database right 2016. Bruce Napier at BGS is acknowledged for the initial construction of the Lithoframe 1:1 M model. This paper is published by permission of the Executive Director of the British Geological Survey (NERC).

Competing interests
The authors declare that they have no competing interests.

Availability of data and materials
The analyses in this paper are based on datasets held by the British Geological Survey. Many of these are available through BGS's OpenGeoscience initiative; see http://www.bgs.ac.uk/opengeoscience/ for more detail.

Consent for publication
Permission to publish has been obtained from our Institution, the British Geological Survey.

Funding
This work was funded from the National Capability funds of the British Geological Survey.

Publisher's Note
Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Received: 24 February 2017 Accepted: 8 June 2017
Published online: 16 June 2017

References

AGRCC (Australian Geothermal Reporting Code Committee). Geothermal lexicon for resources and reserves definition and reporting. 2nd ed. Adelaide: Australian Geothermal Reporting Code Committee; 2010.
Atkins. Deep geothermal review study, final report. Department of Energy & Climate Change (DECC); 2013. p. 142.
Barker JA, Downing RA, Gray DA, Findlay J, Kellaway GA, Parker RH, Rollin KE. Hydrogeothermal studies in the United Kingdom. Q J Eng Geol Hydrogeol. 2000;33:41–58.
Baujard C, Genter A, Graff J-J, Maurer V, Dalmais E. ECOGI, a New Deep EGS Project in Alsace, Rhine Graben, France. In: Proceedings world geothermal congress, Melbourne; 2015. p. 6.
Beamish D, Busby J. The cornubian geothermal province: heat production and flow in SW England: estimates from boreholes and airborne gamma-ray measurements. Geotherm Energy. 2016;4:25. doi:10.1186/s40517-016-0046-8.
Beardsmore GR, Rybach L, Blackwell D, Baron C. A protocol for estimating and mapping global EGS potential. GRC Trans. 2010;34:301–12.
Beardsmore GR, Rybach L, Blackwell D, Baron C. A protocol for estimating and mapping global EGS potential. Version 1.1. Unpublished, May 2011.
Blackwell DD, Negraru PT, Richards MC. Assessment of the Enhanced geothermal system resource base of the United States. Nat Resour Res. 2007;15:283–308.
Bowen DQ, Phillips FM, McCabe AM, Knutz PC, Sykes GA. New data for the last glacial maximum in Great Britain and Ireland. Quat Sci Rev. 2002;21:89–101.
Breede K, Dzebisashvili K, Liu X, Falcone G. A systematic review of enhanced (or engineered) geothermal systems: past, present and future. Geotherm Energy. 2013;1:27.
Bullard EC, Niblett ER. Terrestrial heat flow in England. Monthly notices of the royal astronomical society. Geophys Suppl. 1951;6:222–38.
Busby J. Geothermal prospects in the United Kingdom. In: Proceedings world geothermal congress, Bali; 2010. p. 7.
Busby J. Geothermal energy in sedimentary basins in the UK. Hydrogeol J. 2014;22:129–41.
Busby JP, Gillespie M, Kender S. How hot are the Cairngorms? Scott J Geol. 2015;51:105–15.
Busby J, Kingdon A, Williams J. The measured shallow temperature field in Britain. Q J Eng Geol Hydrogeol. 2011;44:373–87.
Busby J, Lewis M, Reeves H, Lawley R. Initial geological considerations before installing ground source heat pump systems. Q J Eng GeolHydrogeol. 2009;42:295–306.
Clauser C. Geothermal energy. In: K. Landolt-Bornstein, Group VIII: Advanced Materials and Technologies, energy technologies, Subvol. C, Heinloth (ed). Renewable energies, Heidelberg: Springer; 2006; 3:493–604.
Cornwell JD, Walker ASD. Regional Geophysics. In: Jones DG, editor. Plant J A. Institution of Mining and Metallurgy/British Geological Survey: Metallogenic models and exploration criteria for buried carbonate-hosted ore deposits—a multidisciplinary study in eastern England; 1989. p. 25–51.
Downing RA, Gray DA, editors. Geothermal energy—the potential in the United Kingdom. London: HMSO; 1986a.
Downing RA, Gray DA. Geothermal resources of the United Kingdom. J Geol Soc Lond. 1986b;143:499–507.
Gale IN, Rollin KE. Assessment of the geothermal resources. In: Downing RA, Gray DA, editors. Geothermal energy—the potential in the United Kingdom. London: HMSO; 1986. p. 132–47.
Knapek E, Kittl G. Unterhaching power plant and overall system. In: Proceedings European geothermal congress 2007, unterhaching, Germany; 2007. p. 4.
Lee MK, Brown GC, Webb PC, Wheildon J, Rollin KE. Heat flow, heat production and thermo-tectonic setting in mainland UK. J Geol Soc Lond. 1987;144:35–42.

Limberger J, Calcagno P, Manzella A, Trumpy E, Boxem T, Pluymaekers MPD, Van Wees J-D. Assessing the prospective resource base for enhanced geothermal systems in Europe. Geotherm Energy Sci. 2014;2:55–71.
Lukawski MZ, Anderson BJ, Augustine C, Capuano LE Jr, Beckers KF, Livesay B, Tester JW. Cost analysis of oil, gas, and geothermal well drilling. J Petrol Sci Eng. 2014;118:1–14.
Mathers SJ, Terrington RL, Waters CN, Leslie AG. GB3D—a framework for the bedrock geology of Great Britain. Geosci Data J. 2014;1:30–42.
MIT (Massachusettes Institute of Technology). The future of geothermal energy: impact of enhanced geothermal systems (EGS) on the United States in the 21st century, US Department of Energy, Washington, D.C. 2006. https://energy.mit.edu/wp-content/uploads/2006/11/MITEI-The-Future-of-Geothermal-Energy.pdf. Accessed 14 Jun 2017.
Morton D, Rowland C, Wood C, Meek L, Marston C, Smith G, Wadsworth R, Simpson IC. Final report for LCM2007—the new UK land cover map. CS technical report no 11/07, centre for ecology and hydrology (NERC). 2011.
Rollin K. Assessment of BGS data for ground source heat pump installations in the UK. British geological survey internal report, IR/02/196. 2002.
Rollin KE. A simple heat-flow quality function and appraisal of heat-flow measurements and heat-flow estimates from the UK geothermal catalogue. Tectonophysics. 1995;244:185–96.
Rybach L. The future of geothermal energy and its challenges. In: Proceedings world geothermal congress 2010, Bali, Indonesia; 2010. p. 4.
SKM (Sinclair Knight Merz). Geothermal energy potential: Great Britain and Northern Ireland. Sydney: Sinclair Knight Merz; 2012. p. 148.
Vosteen H-D, Schellschmidt R. Influence of temperature on thermal conductivity, thermal capacity and thermal diffusivity for different types of rock. Phys Chem Earth. 2003;28:499–509.
Waples DW, Waples JS. A review and evaluation of specific heat capacities of rocks, minerals and subsurface fluids. Part 1: minerals and nonporous rocks. Nat Resour Res. 2004;13:97–122.
Westaway R, Bridgland DR. Relation between alternations of uplift and subsidence revealed by late cenozoic fluvial sequences and physical properties of the continental crust. Boreas. 2014;43:505–27.
Westaway R, Younger PL. Accounting for palaeoclimate and topography: a rigorous approach to correction of the British geothermal dataset. Geothermics. 2013;48:31–51.
Wheildon J, Francis MF, Ellis JRL, Thomas-Betts A. Investigation of the SW England thermal anomaly zone. CEC final report, contract no 097-76 EGUK, 568-78-1 EGUK; 1981. p. 410.
Whittaker A, editor. Atlas of onshore sedimentary basins in England and Wales: post-Carboniferous tectonics and stratigraphy. Glasgow: Blackie; 1985.
Younger PL, Gluyas JG, Stephens WE. Development of deep geothermal energy resources in the UK. Proc Inst Civ Eng. 2012;165(EN1):19–32.
Zimmermann G, Tischner T, Legarth B, Huenges E. Pressure dependent production efficiency of an enhanced geothermal system (EGS): stimulation results and implications for hydraulic fracture treatments. Pure Appl Geophys. 2009;166:1089–106.