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The theoretical potential for large-scale underground thermal energy storage (UTES) within the UK

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ABSTRACT

Large scale storage of heat is critical for the successful decarbonisation of the UK's energy mix and for grid-balancing. Heat generation currently accounts for 50% of all energy use in the UK and most of this is produced by burning fossil natural gas. Heat is regarded as a single-use commodity, discarded or dissipated when not required in summer yet a lifesaving necessity during the colder winter months. Here we estimate the theoretical potential capacities for the storage of heat in the subsurface using aquifers and flooded mines, with a consideration of seasonal storage of heat in particular. We set this against the theoretical potential volumes of waste heat and solar thermal energy that could be exploited. This contributes to the wider knowledge base of the capacity of different forms of energy storage available through other means and highlights the potential for the UK.

Our calculations indicate that the theoretical potential for large-scale underground thermal-energy storage in the UK is substantial, much larger than which might ever be needed and the location of such storage is well matched to the places where people live and work and therefore where the demand for heat occurs.

1. Introduction

The aim of this study was to examine what potential exists in the UK for underground, thermal energy (heat) storage (UTES) in geological storage facilities including a variety of aquifers and abandoned, flooded mines. The scale of electricity storage in 2020 for the UK is estimated at a scale of <100 GWh capacity for all non-fuel storage technologies such as batteries and hydro pumped water storage. Increases in hydro pumped storage is limited by the number of appropriate sites, but electrochemical storage is expected to become the technology with the largest power and energy capacity once the deployment and vehicle to grid control of millions of electric vehicles has happened. These areas have been the focus of innovation and deployment for many years. In comparison, within the UK, UTES has been largely overlooked in research, innovation and deployment, such as in the case of mines, 'built' over centuries of mining but as yet not commissioned specifically for the storage of heat. The concept shown here develops further the idea presented by Van Ree and van Beukering (2016) of 'Geosystem Services' in which the capacity of the subsurface to supply materials (including energy) for human use needs to be balanced against the impact of use in order to deliver sustainable development. Here we examine the opportunity for recharging subsurface heat from surface activity both human and natural. The requirement for energy storage in a decarbonised, sustainable world is critical as many low-carbon sources of energy have variable output (wind and solar energy) or are operated in a way that prefers a less flexible or more constant output (nuclear fission) and therefore meeting demand with supply requires flexibility of different scales and characteristics. Moreover, given that all energy transitions and many other processes generate (or consume) heat and in many instances, heat is the main, albeit previously unwanted, product, it would be both profligate and unsustainable not to make the best use of available heat. Elsewhere in the world substantial UTES are well developed. Fleuchaus et al. (2018) report that in 2018 there were more than 2800 UTES schemes worldwide abstracting 2.5 TWh of heating and cooling per year with 85% of schemes having been developed in the Netherlands and 10% in Sweden, Denmark and Belgium. The schemes developed in the Netherlands include the mine water based heating and cooling developed in Heerlen (Verhoeven et al., 2014) which acts as an exemplar for possible developments in the UK. Our approach in this paper is to calculate the theoretical heat storage resource rather than determine the heat storage reserve. That is to say we are not at this stage considering the economic or technology hurdles and limitations that need to be considered when generating a reserve figure for

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stored heat potential. Nonetheless we do consider the spatial relationship between where heat can be stored and where heat demand occurs.

It is well understood that to meet its legally binding reductions in the emissions of greenhouse gases it is essential that the UK decarbonises its heat demand, as currently this is predominantly supplied by fossil fuels, largely natural gas. A significant challenge of this decarbonisation of heat when using electrical technology such as heat pumps, hybrid-heat pumps or resistive heaters is the scale of the seasonal and overnight variation in demand that is currently mostly accommodated through the natural gas system. Subsurface thermal energy storage may provide a scalable store for heat to help accommodate greater levels of renewable generation, and also provide a primary source of heat energy too. Here, we highlight the potential of the UK subsurface to help the nation meet its greenhouse gas emission reduction targets.

2. Heat use and existing heat supply

Approximately half of all energy in the UK is used for heating. Those in the south of the nation use a little less than 50% and those in the north more than 50%. This is similar to many other nations with a temperate climate in northwest Europe. However, the manner in which the UK heats its homes is dissimilar to most countries in Europe insofar as domestic heating and cooking is heavily dependent on fossil natural gas (Gross and Hanna, 2019). For the UK about 77% of heating is supplied by the combustion of fossil fuels, almost entirely natural gas (Gluyas et al., 2018). Much, 66% of the heat is generated by burning gas, plus minor oil or coal in homes with the remaining 11% coming from the use of electricity, under half of which is generated from gas fired power stations with unabated emissions of carbon dioxide (Gluyas et al., 2018). There has been a significant but temporary decline in the use of gas in industry during the first half of 2020 in part due to the impact of the Covid19 pandemic, whereas coal is accelerating off the system. By early June 2020 the UK had not used coal for electricity generation for two months and the combined use of coal and gas dropped to below 33% of all generation for the first half of 2020, a new record low. Nonetheless, taken as a whole, heating demand in the UK contributes over one third of the nation's emissions of greenhouse gases, which is why it is essential to decarbonise heating to reach net zero.

Decarbonisation of the electricity grid in the UK is well underway (Crossland and Gluyas, 2019). Plans have also been made to decarbonise transport (GOV.UK, 2020a) but decarbonisation of heat in the UK has hardly begun despite its significant contribution to UK emissions of greenhouse gases. Decarbonisation of heat in the UK therefore means that use of fossil natural gas has to reduce dramatically and most likely cease altogether if the UK is to meet its commitment to have net zero carbon emissions by 2050 (GOV.UK, 2019). In 2019 the Chancellor of the Exchequer announced that by 2025 new domestic properties should not be fossil-fuelled, effectively banning domestic gas connections to a natural gas grid. The legislation for this was to be included in a Future Homes Standard, and the announcement put the heat sector on notice that alternatives for heat generation are required urgently. Current thinking in the UK indicates that heat will in future be supplied by a combination of low carbon electricity, bioenergy, hydrogen and heat networks (utilising waste industrial heat) coupled with demand reduction from improved insulation (BEIS, 2018) and increased amounts of thermal storage. Use of solar thermal energy and low-enthalpy geothermal heat were omitted from the BEIS (2018) document yet both have the potential to play a much more significant role in heat decarbonisation; geothermal because of its ultra-low carbon footprint, large scale and coincident geographical location between potential sites of heat delivery and high-demand areas (Gluyas et al., 2018) and solar thermal as it can be deployed alongside or integrated with photovoltaic (PV) electricity generation (Herrando and Markides, 2016) and also with geothermal seasonal storage. The UK's largest mine-water heating scheme of 3.6 MW is operational at Lanchester Wines in Gateshead (Tighe, 2019) and work has already begun at four more sites in the NE England to supply heat from water in abandoned and flooded coal mines (at Seaham, Gateshead, Hebburn and Stanley (Hancock, 2020; Richter, 2020; Geodrilling, 2020) as well as a major research programme based on extracting heat from abandoned mines in Glasgow (Adams et al., 2019).

Driven by the temperature difference between summer and winter, the demand for space heating and cooling in the UK is highly seasonal. In comparison, the heat demand for hot water is relatively constant across the seasons. Both space heating and hot-water are highly variable over the course of a day, with typical aggregated patterns of demand following a double peak centred on the morning at 8 am and in the evening at 6–8 pm. However, it is the demand for space heating that drives the largest seasonal swing in primary energy demand for the UK, which manifests itself through the variation for natural gas demand. Fig. 1 shows the daily total demand for natural gas, for liquid fuels (petrol, diesel and aviation fuel), for electricity and the daily supply of low-carbon electrical energy (wind, solar, nuclear, biomass, hydro). Although the values for liquid fuels are only available at a monthly level (BEIS, 2019a), and will thus mask sub-monthly variations, it is clear from Fig. 1 that the natural gas demand has the highest seasonal primary energy variation in absolute terms (as well as relative terms too). The daily demand for natural gas in Britain was almost 5000 GWh on the 1st of March 2018 due to a significant but short lived cold weather event late in the heating season. In comparison, in the summer of 2019, the daily natural gas demand nearly dropped to 1000 GWh per day. Therefore, the natural gas demand seasonal variation can be as much as 4000 GWh per day between the highest daily demand in winter and lowest daily demand in the summer. The equivalent for the electrical system is circa 500 GWh per day between the highest (1100 GWh) and lowest (600 GWh) daily demand values, and for liquid fuels is circa 300 GWh per day between a high of 1800 GWh per day and low of 1500 GWh per day. Comparison of these values confirms that the seasonal variation in gas demand is the major source of variation across any of the UK's energy networks and highlights the scale of the challenge of using electrification alone to decarbonise heat.

Looking over a longer timeframe and using monthly rather than daily data from Energy Trends 4.2 (BEIS, 2020) Fig. 2 shows that the natural gas system has the capacity to cope with a seasonal swing for natural gas demand between highs of circa 130,000 GWh per month in January 2001, 2010 and December 2010, and lows of circa 33 GWh per month in August 2013. This seasonal variation is an important consideration when considering the shift to low-carbon heating (Wilson et al., 2013). The UK currently imports greater levels of primary energy over the heating season (in the form of natural gas) and can be thought to have offshored the seasonal flexibility of its primary energy demand to an international supply chain.

As a country with a temperate climate, the seasonal demand for space heating (winter) is out of phase with the greater availability of heat and electricity generation from solar thermal and photovoltaic panels for which the summer months are the most productive. To an extent the out of phase nature of supply and demand is true for using waste heat from industry, but over shorter timeframes e.g. within a day. Thus, many developments for improved low-carbon heating systems hoping to exploit these sources of heat would benefit from storage at a range of scales such as overnight, within day and inter-seasonal heat storage to decouple the supply into the time of day/year when demand is higher (Renaldi and Friedrich, 2019).

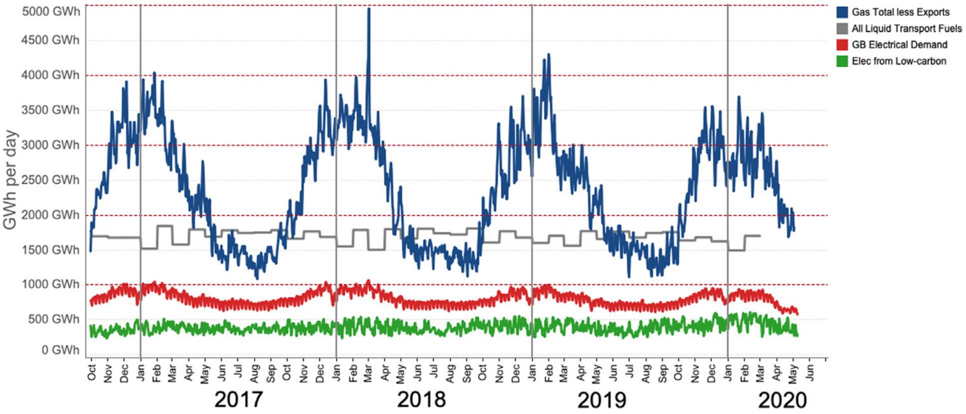

Fig. 1. GB Natural gas, liquid fuels and electrical demand, and low-carbon generation.

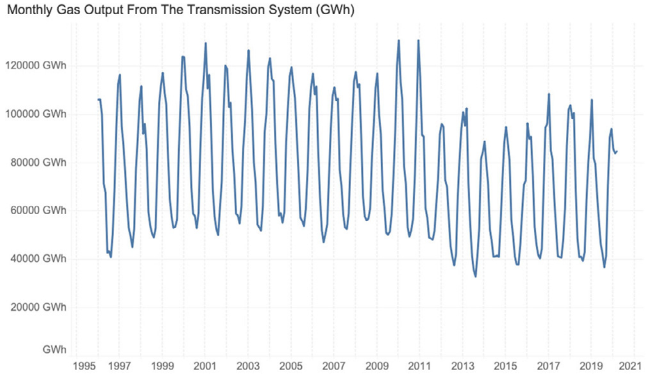

Fig. 2. GB Natural gas, monthly output from the transmission system.
Source: Data from BEIS (2020).

3. Low-carbon heat sources

The three main under exploited sources for low-carbon heat in the UK are geothermal systems, including flooded abandoned mines, waste heat from industry and solar thermal. Geothermal energy is little used in the UK with two systems operating. The largest produces a thermal output of 3.6 MW and is a commercial mine energy system installed at bonded warehouses in the Tyne and Wear region (Tighe, 2019). The Southampton scheme is the only operational district heating system coupled to a deep geothermal source in the UK (Gearty et al., 2008). The Southampton District Energy Scheme (Fig. 3) combines geothermal and gas-fired power generation to supply heat and power to the central part of the city. The scheme draws brine from the deep saline Sherwood Formation (Triassic) at about 2 km below surface and at a temperature of 75 °C and rejects spent water to the English Channel at about 50 °C (compliant environmentally), delivering 1.7 $\mathrm{MW_{TH}}$ into the adjacent hospital, university and retail sites (Gearty et al., 2008). Elsewhere in the UK much of the current effort has been focused on developing ultra-low enthalpy schemes based upon extraction of water from flooded mines. The most advanced of these are in North East England as mentioned above and together with initiatives in South Wales, County Durham (where drilling has begun, Fig. 4), Tyne and Wear, Northumberland and Nottingham the UK could by the mid-2020s have between 5 and 10 operating systems each delivering 2–5$\mathrm{MW_{TH}}$.

The UK's potential for development of geothermal heat is substantial and includes several settings; flooded coal mines, buried cave systems, deep permeable saline aquifers and naturally fractured and thus permeable radiothermal granites. The thermal gradient in the UK varies from about 35 to 25 °C km^{-1}. The higher gradients are typically associated with the Permian granites of Cornwall and Devonian granites of southern Scotland and Northern England. With a surface temperature of around 10 °C, the subsurface of the UK reaches about 50 °C between 1 km and 1.5 km and 100 °C at 3 km to 4 km. Gluyas et al. (2018) calculated that the resource could supply all of the UK's heating needs for a minimum of 100 years (300×10^{18} J, 83,333 TWh). This assumes that the warm water in which the heat is stored is simply abstracted with no replacement of cooled water to be reheated. Sustainable management of the resource would include reinjection of spent cooled water to be reheated by the rock and remaining connate water. Appropriate management of abstraction and re-injection could potentially deliver an inexhaustible supply of heat providing that replenishment rates of heat flow from the Earth's interior are not exceeded. Moreover, much of the resource is co-located with areas of high population density. Many of the UK's towns and cities were built on sedimentary basins and many of those basins also contain mined coal deposits.

The co-location of heat demand in the brownfield areas that were once coal mining districts and hence now hold a heat resource within the flooded mines has already been shown to provide socio-economic opportunities beyond supply of heat by the Heerlen development in Limburg, Netherlands (Verhoeven et al., 2014). At Heerlen, development of the mine-energy underpinned regeneration of an economically depressed area after cessation of coal extraction. The initial investment attracted further inward investment into the area. As yet unpublished studies by researchers at Durham Energy Institute (Goodman, 2018) are showing that former mining communities in County Durham UK are welcoming the opportunity to rebuild around community based mine-energy projects.

The UK's Business, Energy and Industrial Strategy Department report that there are approximately 17,000 heat networks in the UK providing heat to about 450,000 homes but only 2% use waste heat from industry (BEIS, 2019b). Bennett et al. (2020) estimated the total waste heat produced per annum in the UK industry to be about 46,000 GWh and the power sector to be about 210,000 GWh. Some of this heat is irreclaimable, such as that from welding car bodies and some is already used, for example in pre-heating for the calcination process in cement production but the vast majority of the waste heat is simply removed by dissipation in air or water. The waste heat streams include that from electricity generation (from coal, natural gas, waste, nuclear, photovoltaic panels), the petrochemical industry, dairies, breweries and other food manufacture, iron and steel production, cement and ceramics and data centres. The heat so produced is often high-grade (temperatures may exceed 1000 °C) but has specific, rather than distributed locations.

Fig. 3. Southampton District Energy Scheme operational base. The geothermal production well lies behind the building with the wellhead and associated instrumentation occupying an area of about 25 m^2. The photograph demonstrates the modest surface footprint of a combined geothermal heat and power plant in a city centre location and absence of emissions commonly associated with a power station (photograph J. Gluyas)

Fig. 4. Drilling at the Louisa Centre, Stanley, County Durham (October 2019). The well drilled into the former workings of the Louisa Mine from which water will be pumped to heat the adjacent swimming pool. The modest scale of the operation which is the size of a couple of parking spaces in the Louisa Centre's car park is clear from the photograph (photograph S. McDonald).

Table 1
Developed areas of the UK, percentage data from Rae (2017).

Land category	Percentage of UK land (%)	Area (km^2)	Area of possible solar thermal deployment (km^2)
Discontinuous urban fabric	5.3263	13,184	423
Continuous urban fabric	0.1320	327	
Sport and leisure facilities	1.1474	2 840	284
Industrial or commercial units	0.8227	2 036	207
Airports	0.1993	493	99
Road and rail networks	0.0492	122	24

In addition to geothermal and waste heat, little planned use is made of the thermal heat arriving from the sun. The incident solar flux for the UK averages about 100 Wm^{-2} (equivalent to about 0.877 MWh per year per square metre), higher in southern England and lower in northern Scotland (MacKay, 2013). The flux varies annually from around 20% of the mean in mid-winter to double that of the mean in high summer and daily between a peak at midday and zero during the hours of darkness. It is thus completely out of phase with consumption of natural gas that peaks in winter. Also, the local gas demand, which contains the fraction of natural gas for domestic properties, commercial and service sectors, has a double peak and a pronounced trough in demand over the middle of the day; the morning peak is centred at 8 am and evening peak around 6 pm–7 pm (Wilson et al., 2018). Again, neither of these are well aligned with when the solar resource is at its highest, suggesting some form of storage to help to match available supply and demand.

To calculate how much of this heat could be harvested we used the Land Cover Atlas of the United Kingdom (Rae, 2017). The land area of the UK is about 247,526 km^2. The percentages of developed land and their areas are listed in Table 1.

In order to determine how much heat could be harvested from the space recorded in Table 1 a number of assumptions are required. Considering both the continuous and discontinuous urban fabric, only a small portion of this would be available for deployment of solar thermal devices because much of the space will be occupied by open green spaces, gardens, roads, wrongly orientated roofs and so on. To calculate the available space we have used ONS data on numbers of homes and average house footprint size. There are about 25 million homes in the UK and according to the UK's Office of National Statistics (ONS, 2020) with an average building footprint of 85 m^2. Approximately 2 million have either solar photovoltaic (>1.5 million) or solar thermal panels already fitted and about 82% of people live in towns and cities. Together these equate to approximately 18.9 million homes in urban settings but lacking current use of the roofs. Up to 75% of such homes would not be suitable for solar thermal device deployment because of their inappropriate orientation. Thus, a maximum of 25% of urban homes could have solar thermal panels fitted and this equates to 423 km^2.

It is much more difficult to determine what proportion of either sports facilities or industrial units could be instrumented with solar thermal devices. Individual sports halls may be large but likely modest relative to the outdoor space. As such we have used 10% of the space occupied by sports and leisure facilities as capable of hosting solar thermal devices. For industrial units we have worked the calculations based upon 20% of space being available for installation of solar thermal devices. Airports and road infrastructure are treated in the same way with an estimated 20% of the area occupied could be used for solar thermal installations. For roads and runways, the heat collection would be from beneath the surface.

In total a little over 1000 km^2 of roof and ground space in the UK could be used for heat collection and at 0.877 MWh m^{-2} per annum of solar heat captured across the UK would be 0.909×10^9 MWh about half of which could be stored (50% efficiency). This figure is within a factor of two the same as the total heat used (3×10^{18} J or 0.83×10^9 MWh; Gluyas et al., 2018), although we have not here accounted for losses of heat on storage or the energy required to store and retrieve the heat. What it does demonstrate though, is the small proportion of the sun's heat landing on the UK's landmass which needs to be captured and stored to meet the UK heating demand throughout a year.

The Earth, the sun and waste heat from UK industry individually and collectively could enable the UK to completely decarbonise all of the energy used to heat homes, workplaces and industry in a sustainable and low-impact way. Because heat is also commonly a waste product by using heat more effectively the overall energy demand is lowered. However, heat is not readily portable and demand and supply are not synchronised. In consequence the storage of heat would be required to balance supply and demand over different timeframes including large scale seasonal stores.

4. Large-scale underground thermal energy storage potential of the UK

Large scale underground thermal energy storage requires that a lot of material is available in which heat can be stored and it also necessitates insulation for heat retention. Water has excellent thermal capacity and is present in naturally occurring and man-made subsurface features facilitating both the production and storage of heat. The UK geothermal resource is low enthalpy and best suited to heat production either directly or with heat pumps. Though it is low enthalpy it is widespread and diverse and found in: hot granites >1 km, sedimentary basins >1 km, buried cave systems >1 km, and abandoned mines and petroleum wells, meaning that many areas of the UK could use geothermal to help to decarbonise their heat demands.

In order to calculate the volume of water available for heat storage in the UK we adopted the following approaches:

- The mass of accessible water in the UK's 23,000 flooded mines has been calculated from the mass (volume) of coal mined from which the volume lost by collapse of the overburden has been subtracted. Coal is not the only mineral resource to have been mined in the UK but at 15 billion tonnes (Adams et al., 2019) the volume mined dwarves other minerals such as salt, lead, tin, iron and copper. The quantity of void space left after mining and collapse depends upon the mining method. Former room and pillar mines retain about 50% of the mined coal volume as void space while for longwall mining the residual void space is about 20% of the mined coal volume (Adams et al. *op cit*). We have made the conservative assumption that the average remaining void space equates to 25% of the former coal volume. Given that the average specific gravity of the UK's bituminous coal is around 1.346 then the approximate mass of water lying in abandoned mines in the UK is about 2.79 billion tonnes.
- The mass of potable water in UK aquifers was calculated by the UK Groundwater Forum (undated 'a' reference) at 40 billion tonnes for the interval between the ground surface and 20 m below the surface (unconfined zone). In the same document, the deeper confined aquifers were estimated to be around 800 billion tonnes. These figures only relate to 5 of the six major UK aquifers: Cretaceous Chalk and Greensand, Jurassic limestones, Permo–Triassic sandstones and the Permian Magnesian Limestone (Allen et al., 1997). The Carboniferous Limestone was not included in this calculation nor the UK's minor aquifers (Jones et al., 2000).
- We have not found any assessment of the mass of water in deep saline aquifers of the UK but data do exist for the geothermal resource of deep saline, Permo–Triassic, sandstones in England and Northern Ireland (Rollin, 1995; Busby, 2010, 2014) at 327×10^{18} J. The resource was calculated on the basis of mean temperatures in deep sedimentary basins with Permo–Triassic sandstones and a defined rejection temperature of 40 °C. From the data in Busby (2014) it is possible to calculate the mean temperature for Permo–Triassic sandstones in UK basins, weighted by area and this volume of the sandstones as 65 °C. That is to say that the 327×10^{18} J (91 000 TWh) resource was calculated on the basis of a 25 °C temperature drop. Data in Table 2 for deep saline aquifers are derived from the 327 EJ figure using smaller temperature drops of 1 °C, 2 °C, 5 °C and 10 °C. The water volume in the deep saline Permo–Triassic aquifer has been derived in the same way.

Table 2 combines the storage capacity of flooded mines, confined and unconfined potable aquifers (5 from 6 major UK aquifers) and the deeper geothermal resource from the Perm–Triassic aquifer alone for 1 °C, 2 °C, 5 °C and 10 °C increases in temperature. The available unused heat resource from solar thermal and waste heat is also included in Table 2 as is the annual heat demand for the UK. The combined heat from waste and potential solar thermal is comparable to heat demand and the mass of water in flooded mines and potable reservoirs need only be raised by around 1 °C to store that heat on a seasonal basis. If deep saline aquifers are included then 0.1 °C temperature elevation will suffice. In practise, only a small fraction of subsurface water in any area underlying towns and cities is likely to be used for heat storage and hence temperature rises would be significantly more than 0.1 °C. All we have attempted to do with this calculation is to demonstrate that the subsurface resource of water is vast and, in many areas, perfectly capable of storing substantial quantities of heat without requiring massive temperature increases.

5. Spatial distribution of heat users and heat storage

Heat is less transportable than fuels, meaning there is unlikely to be an international market which transports heat around the globe if fuels can be utilised to achieve the same end. The same is

Table 2
Heat storage capacity of subsurface water in the UK, unharvested UK heat (solar thermal and waste heat) and UK heat demand.

Storage unit, source and demand	Water mass (T × 10^9, billion)	Available energy (J × 10^{12}) [10^{12} J = 0.0002777 TWh]				
		1 °C	2 °C	5 °C	10 °C	Source heat
Abandoned mines	3	1.17×10^4 [3.25]	2.31×10^4 [6.41]	5.83×10^4 [16.19]	1.17×10^5 [32.49]	
Potable aquifers (<20 m)	40	1.67×10^5 [46.4]	3.35×10^5 [93.0]	8.37×10^5 [232]	1.67×10^6 [464]	
Potable aquifers (>20 m)	800	3.35×10^6 [930]	6.69×10^6 [1860]	1.67×10^7 [4650]	3.35×10^7 [9300]	
Deep saline aquifers	3126	1.31×10^7 [3638]	2.62×10^7 [7276]	6.54×10^7 [18 189]	1.31×10^8 [36 380]	
Total subsurface capacity	**3968**	**1.66×10^7** [**4609**]	**3.32×10^7** [**9220**]	**8.30×10^7** [**23 049**]	**1.66×10^8** [**46 090**]	
Waste heat						1.66×10^5 [46.09]
Solar thermal (1000 km^2)						3.27×10^6 [908]
Demand						**3.00×10^6** [**833**]

true on a national or even regional scale. Excepting smaller scale heat storage using phase change and other materials, which can be transported (Pielichowska and Pielichowski, 2014), thermal energy storage and retrieval in underground mines and aquifers must therefore focus on a local or regional scale. In consequence it is imperative to compare the distribution of users and areas suitable for underground thermal energy storage. This we have done this for the UK by comparing the distribution of abandoned coal mines, major and minor aquifers (shallow potable and deeper saline aquifers) and with heat demand density maps for Scotland and London and for the rest of the UK's population density map as currently, the UK government does not publish a national map (Figs. 5 and 6).

The spatial match between where heat demands occurs, that is where people live and work, and the distribution of potential storage sites is very good. This is in part a self-fulfilling process since in the UK many towns and cities were built on areas of sedimentary rock, or more particularly where coal was mined. Indeed 25% of all UK homes and businesses lie within the area of mined coal fields. These same areas are also where waste heat is produced from industry and where the built-environment could be adapted to trap solar heat.

6. Discussion

The high-level, nation-scale analysis presented demonstrates that naturally occurring aquifer and 'built' or rather mined underground thermal energy storage capacity in the UK is of a scale perfectly capable of storing heat for use by the vast majority of the UK population. We have also identified a significant quantity of waste heat and solar energy that could be stored in these locations. Our analysis includes estimates of the total water mass in a variety of major and minor aquifers containing potable water and deep saline aquifers that are a major source of heat as well as having storage capacity. While it is clear that not every part of all aquifers would be used there are plenty of underground water bodies which potentially could be used. We have also included aquifers that are used for domestic supply. Here the expected temperature increase is sufficiently low, around a few degrees centigrade, that there is little downside risk and an upside bonus that should such water be delivered to homes it would marginally reduce the energy required to further heat the water for bathing, washing and cooking.

The small city of Heerlen in Limburg, Netherlands has developed a city-wide heat supply and storage system which uses the abandoned coal mines beneath the city (Verhoeven et al., 2014). Water is circulated at 28 °C, the ambient temperature of the deepest of the mine levels; pipework is uninsulated and heat losses tiny. The scheme covers an area of around 12 km^2 and has been operational for almost 20 years. Due to its success and increasing numbers of customers, the operators are now looking to inject and store waste heat within the mine to increase the available recoverable heat. The re-commissioning of the old mines for heat storage and supply in Heerlen has had some profound impacts. Energy security has been increased; investment in Heerlen has attracted further inward investment and the economic fortunes of what was a socially depressed area revived. At the same time the local carbon emissions have been greatly reduced. This provides a potential blueprint for areas within the UK but requires detailed analysis to understand which areas these might be.

Detailed analysis of candidate areas is required for storage and resource availability, as the physical dispersion of the stored heat has to be known; the heat can be put into one part of a system and naturally shift with a movement of the water to a different location. This can be less of a problem if the location is well understood, but clearly poses an additional risk to any project if there is uncertainty surrounding this.

The UK does not currently have a legislative framework for licencing the subsurface for heat abstraction or heat storage nor does it have a system to regulate heat trading. The Environment Agency licences abstractions from and re-injection to surface and groundwaters. These licences are generally based around consumptive uses and the existing licencing regime is under review to better include accommodate projects. There is currently no ombudsman for heat and consumers on heat networks may find themselves at the behest of the network operator in terms of heat pricing though common sense suggests this would have to be lower than the counterfactual to attract customers initially. For lower temperature ambient loop systems this "lock-in" can be less of a problem because consumers may have their own heat pumps at point of use with the flexibility to change electricity supplier. Common use fuels such as natural gas, oil, coal and electricity are sold by volume (gas and oil), weight and as kWh respectively. Production of non-potable geothermal water would presently fall under potable water abstraction rules. The Coal Authority which has responsibility for all 23,000 abandoned

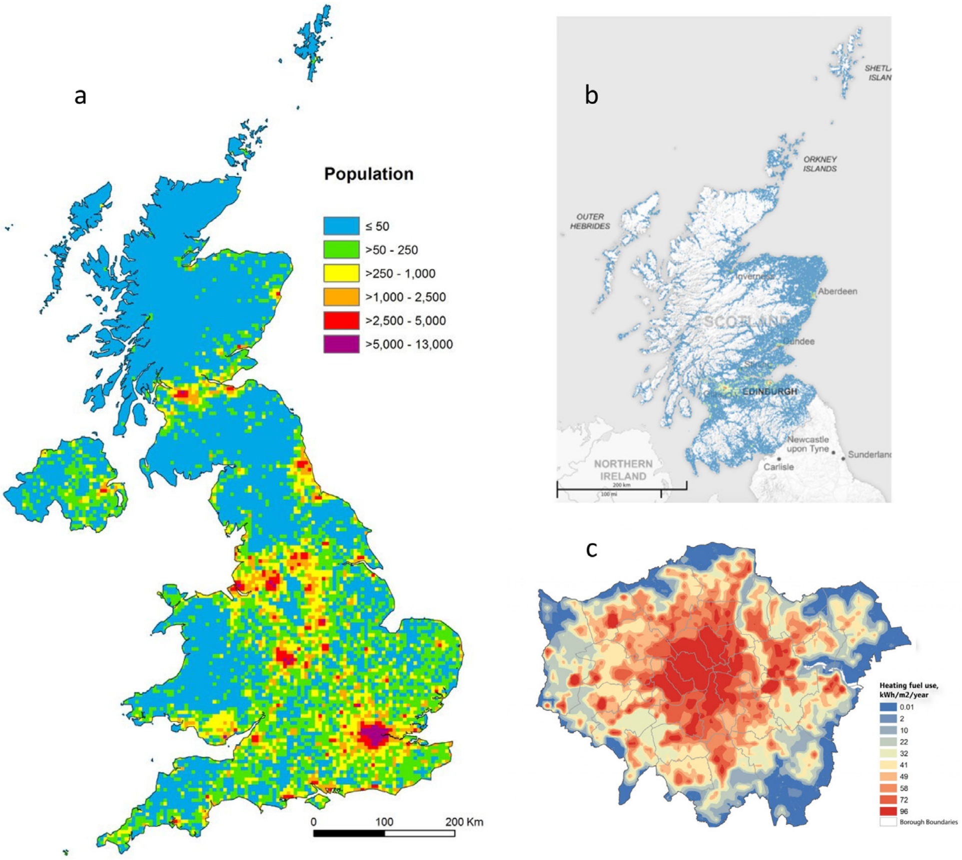

Fig. 5. Heat demand in the UK, (a) population density of the UK (from Vieno et al., 2016), (b) Heat demand density map for Scotland (from http://heatmap.scotland.gov.uk), (c) Heating fuel use London (from Greater London Authority, 2011).

mines and associated infrastructure in the UK is currently investigating how it might licence abstraction of water and thus heat. Representation to the UK parliament and government by Durham Energy Institute since 2015 has brought the geothermal opportunity into the energy debate and this has helped activate a positive response from the UK research councils and the Department for Business, Energy and Industrial Strategy but to date we are not aware that UTES has received significant attention.

We have not attempted to calculate the cost and payback time for heat storage schemes in the UK. Over the past decade or more the fiscal support from government in the form of the renewable heat incentive (RHI) for low carbon heat projects has helped to stimulate interest however its imminent review with lack of clarity over its future form and function threatens the business case for many of the mine energy projects currently in planning.

One such case is the Louisa Centre, Durham which showed that when RHI support was withdrawn the forecast payback time for that particular project jumped form 2 years to about 20 years (pers comm S. Macdonald July 2020). Fleuchaus et al. (2018) report from their global study that typical paybacks range from 2 to 10 years and with capital expenditure ranging from €0.2 million for small systems to € 2 million for larger ones.

7. Conclusions

The mismatch between the solar resource in the UK in the summer, the vastly increased demand in winter for heat and the significant but variable sources of waste heat available suggest that seasonal storage will be an essential component of a future balanced, low-carbon energy supply system. This would facilitate better use of solar energy harvested in summer for offsetting shoulder season and winter heat demands. It is clear that the costs of seasonal storage and supply would have to be small on a per unit basis of heat stored to stand any chance of deployment although adding storage to a heat network can improve system economics by allowing more customers to be supplied, and offer wider energy system benefits in terms of flexibility. This is a significant challenge when compared with the cost of deploying nationally subsidised natural gas. Supplementing storage to a mine energy system could also improve its economics firstly by making more of use of low-cost electricity when it is available to pump heat and water in the system, and secondly by improving system coefficients of performance by increasing the source temperature. This would also have a benefit of reducing carbon emissions and improving local air quality. This combined with the need for rapid deployment in order to meet emissions reductions targets suggests that proven technologies and low-cost materials and infrastructure may be more favourable. Scale is also an important factor, so those technologies that provide economies of scale for storing heat offer advantages over those whose costs scale more linearly with size. Underground thermal energy storage in mines is of sufficient scale to warrant more detailed research to better understand what the trade-offs and costs are of using them to store summer and waste heat. In particular, the re-use of coal mines to help support the UK in its transition to a low-carbon energy system provides a means to leverage its legacy 'infrastructure' of abandoned mines.

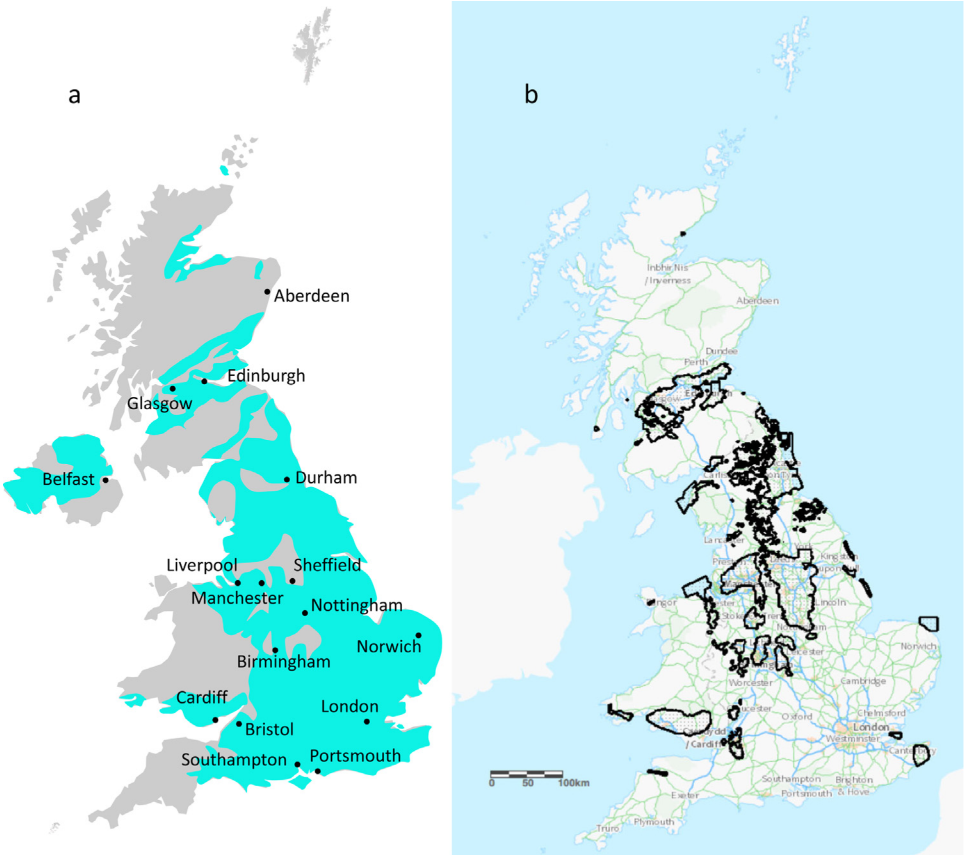

Fig. 6. (a) Composite aquifer map of the UK (compiled from Dochartaigh et al., 2015), Groundwater Forum undated b and the BGS website on Principle Aquifers of the UK, undated, (b) Areas mined for coal in the UK (from UK Coal Authority interactive map).

CRediT authorship contribution statement

J.G. Gluyas: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing. **C.A. Adams:** Conceptualization, Funding acquisition, Investigation, Methodology, Resources, Software, Validation, Writing - original draft, Writing - review & editing. **I.A.G. Wilson:** Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing - original draft, Writing - review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: JGG is a director of GeoEnergy Durham which has earned consultancy fees from work on the heat (abstraction) potential of flooded mines.

CAA is an employee of The Coal Authority which manages the abandoned mines of the UK on behalf of the UK Government.

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Data availability

The data reported in this paper are taken from existing published and available literature. All derivative data are included in the tables.

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