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Assessing the technical potential for underground thermal energy storage in the UK

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ABSTRACT

Heating and cooling both make up a large part of the total energy demand in the UK; long-term seasonal thermal energy storage (STES) can address temporal imbalances between varying supply and demand of heat to buildings and processes. Underground thermal energy storage (UTES) can play a role in energy decarbonisation by storing waste heat from space cooling, refrigeration, data processing, industrial processes, harvested summer solar thermal energy or even heat generated by surplus renewable (solar or wind) electricity with fluctuating supply. This paper evaluates a range of UTES technologies in a UK context and addresses geological suitability, storage capacity, low-carbon heat sources, surface heat sources and demand. This review concludes that there is a significant potential for UTES in the UK for both aquifer thermal energy storage (ATES) and borehole thermal energy storage (BTES) systems, coinciding with surface heat sources and demand. Therefore, uptake in UTES technology will help achieve net-zero carbon neutral targets by 2050.

There is also scope to utilise UTES technologies within existing subsurface infrastructure. There are 464 oil and gas wells which could be repurposed upon end of life using different UTES technologies. However, the potential for repurposing needs further evaluation; deep single well BTES systems will have a high surface area to volume ratio for storage, reducing the efficiency of such systems and the potential for ATES is limited by issues associated with contaminants. 23,000 abandoned mines underlay ~25 % of the UKs population and could be utilised for minewater thermal energy storage (MTES).

1. Introduction

In the UK, there is a significant demand for direct heat use and 73 % of this is supplied by gas [1], contributing to one third of the UK's greenhouse gas emissions. Underground thermal energy storage (UTES) can help to achieve UK government targets of a net zero carbon economy by 2050 and improve energy security. The large demand for heat use in winter and cooling in summer can be met by UTES; UTES in combination with district thermal energy networks, permits the coupling of multiple heat sources and sinks with subsurface storage. Seasonal thermal energy storage (STES) from renewable energy and waste heat can help to meet demand for cooling in summer and heating in winter, concurrently prolonging the lifetime of the deep or shallow geothermal resource. Furthermore, recent investigation has highlighted the UK to have a 'very good' potential for aquifer thermal energy storage (ATES), falling in the top 7 % of regions for ATES worldwide [2].

The objective of this study is, therefore, to assess and review the capability of sensible heat storage (e.g., Ref. [3]) via UTES in the UK. This will focus on ATES, borehole thermal energy storage (BTES) and minewater thermal energy storage (MTES). Whilst other types of UTES exist, such as tank thermal energy storage (TTES) and pit thermal energy storage (PTES), they are less dependent on subsurface conditions and can occupy large surface areas, making them unsuitable for use in densely populated areas. It is also worth noting that there are other methods of thermal energy storage such as latent heat storage, which stores heat via phase changes and thermochemical heat storage, which uses reversible chemical reactions to store heat [4]. These are outside

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Abbreviations:

UTES	Underground Thermal Energy Storage
STES	Seasonal Thermal Energy Storage
ATES	Aquifer Thermal Energy Storage
BTES	Borehole Thermal Energy Storage
MTES	Minewater Thermal Energy Storage
PTES	Pit Thermal Energy Storage
TTES	Tank Thermal Energy Storage
NSTA	North Sea Transition Authority
SSG	Sherwood Sandstone Group
MMG	Mercia Mudstone Group

the scope of this study as they are usually associated to surface storage.

During the late 1970s and 1980s, exploration and evaluation of the deep geothermal potential of the UK was carried out. Interest then waned, to be re-stimulated in the last decade. Downing and Gray [5] conducted a thorough investigation into geothermal resources in the UK highlighting the significant resource potential in both hot dry rocks and hot sedimentary basins. Further investigation has been conducted to assess heat flow, geothermal resources, and demand in the UK for energy [6–12]. A large quantity of data is available for assessment with much listed in the geothermal catalogue for the UK [13–16]. Furthermore, some investigation has been undertaken for the repurposing of oil and gas wells in the UK for energy extraction [17], but not for energy storage.

Whilst limited deep (i.e., >500 m) geothermal development has occurred following initial evaluation, the development of heat pumps has created an increase in the development of shallow (i.e., <500 m) geothermal resources (or "ground source heating and cooling" – GSHC) for both domestic and commercial uses varying in scale up to a few MWs (e.g., Ref. [18]). Ground source heat pumps allow open- and closed-loop systems to be operated at low temperatures for heating and cooling at lower initial capital costs in comparison to deep geothermal developments. Ground source heat pump screening tools have been developed for the UK, advising the suitability of open- or closed-loop developments [19]. The tool considers hydrogeological and economic factors such as aquifer presence, borehole depth, geographical/legal restrictions and water quality information. Whilst intended for heating and cooling use, this can be considered for ATES/BTES development.

To evaluate the capability of UTES technologies in the UK, various aspects must be considered including geological subsurface suitability, heat sources, energy demand and energy affordability for charging. Little attention has been paid to UTES in the UK, particularly in comparison to other European countries, such as the Netherlands (e.g., Ref. [20]). There have been localised modelling studies considering deep single well ATES in the Cheshire Basin, but the storage efficiency was relatively low and due to the large surface storage required for water, it would be unpractical to operate such schemes [21]. Others have investigated open-loop shallow systems in a chalk aquifer in Colchester; highlighting reinjection would improve performance in a heating and cooling system [22]. Shallow open-loop systems have been modelled on the edge of the Cheshire Basin, aiming to remove waste heat from surface users [23]. There are numerous shallow open- and closed-loop geothermal (heat pump) schemes installed in the UK (~37, 000 GSHPs as of 2019 [24]), many of the larger of which incorporate elements of both heat extraction and heat rejection – for example, schemes in Glasgow [25] and Leicester [26–28], among many others. These could thus be said to represent a form of unbalanced UTES, although examples with the aim of deliberately storing waste heat to maximise subsequent recovery as a UTES system *sensu stricto* (e.g., Ref. [29]) are relatively few. As a result, when considering systems for UTES, this study's definition of UTES includes ambient thermal storage systems, high-temperature thermal storage systems and systems that have a *de facto* heat storage aspect as part of a heating and cooling scheme.

The UK is in the course of developing a number of minewater geothermal schemes, utilising heat pumps [30] to supply heat for industrial space heating or district heating (e.g., Refs. [31–33]). None of these can be said to be thermal energy storage schemes, although there is some potential to use flooded mines for MTES either in deep wide shafts or in cases where mine workings are isolated and/or throughflow rates are low.

Important surficial components to STES have also been investigated. When considering the surface demand, Busby [9] highlighted the key surface demand is proximal to the UKs cities such as London, Leeds, Manchester, Birmingham etc., with heat demand density up to 86 kWh/m^2 (per year although not explicitly stated in the study). Albert et al. [34] drew attention to the vast amounts of waste heat in the UK from industrial processes, which was around 391,000 GWh in 2018. There are also significant opportunities to store unused energy generated from renewable resources in the summer when demand is low for heat, such as wind energy and solar, with the average annular solar resource producing $101.2 W/m^2$ [35]. Whilst these papers compile and analyse data on heat demand, waste heat and renewable resource they do not assess it with application to UTES technology regionally across the UK.

There has been significant research (such as modelling studies) identifying the separate integral components of UTES/STES without analysing the combined potential of both the surface and subsurface within the UK. District-scale smart energy systems can be developed with smart applications for STES (e.g.,[36]), but require existing knowledge of local conditions such as waste heat, renewable resources and UTES technologies. Therefore, regional analysis/mapping of different UTES components is required to investigate the potential to couple these. A useful study examined the possibility to develop UTES nationally [37]. They provided analysis on heat use, sources and storage capacities for MTES and ATES technologies. However, they did not investigate other types of UTES technology, the potential for low-cost heat storage (via heat pumps), repurposing of existing infrastructure for storage (such as oil and gas wells), specific renewable sources (including wind curtailment), geological characterisation of thermal stores, and limitations of each UTES technology.

The aim of this paper is, therefore, to provide analysis of site suitability of ATES, MTES and BTES, charged with multiple energy sources, for the UK. A comprehensive and systematic analysis of literature was undertaken from a range of sources and publications. It does focus on resources largely within the public domain, which is thus a limitation, as further UTES sites in the UK will not be captured. Comparisons were made of regional spatial locations of high waste heat, subsurface most suitable for UTES, renewable energy sources with high curtailment (wind) or high energy generation potential (solar), and high energy demand areas. Storage capacities were calculated for BTES and compared to current ATES and MTES estimates. Potential opportunities arising in changing electricity markets were also identified. Low pricing markets created by an oversupply of energy, or low demand, can be used in combination with UTES technologies.

2. Overview of underground thermal energy storage (UTES) systems

In this Section, a range of UTES technologies are outlined indicating applicability, limitations, constraints, and current uptake in the UK. This is compiled from literature with the aim of identifying the key constraints such that this can be applied regionally to the UK subsurface to highlight areas of high potential.

2.1. Borehole thermal energy storage (BTES)

UTES uses the subsurface for thermal storage with heat transfer to and from the surrounding rocks and fluid in the ground (Fig. 1). BTES systems usually use heat pumps and a borehole heat exchanger (BHE) to transfer heat between a circulating fluid and the subsurface, typically, in shallow systems (<300 m depth) often using a u-tube (e.g., Ref. [38]) or co-axial design (Fig. 1b). BTES is less dependent on geology than ATES as it does not require a permeable medium for direct advective heat transfer and can, therefore, be considered in regions unsuited to ATES (e.g., Ref. [39]). Some consideration of geology does need to be undertaken. BTES benefits from a low borehole thermal resistance (thermally efficient borehole, high conductivity materials, backfill or grout), a high ground volumetric heat capacity, moderate ground thermal conductivity (excessively high conductivity might exacerbate conductive heat loss) and minimal groundwater flow (to minimise convective heat losses) [40]. The range of ground thermal conductivity that allows efficient BTES is large, and includes most commonly occurring water-saturated lithologies. High ground thermal conductivity allows more efficient rejection and extraction of heat to-and from-the ground (e.g., Refs. [41–44]), while lower conductivity minimises conductive heat loss from the array during storage [45–48]. The optimal ground thermal conductivity will depend on the mode of dynamic operation of the BTES: high thermal conductivity is likely to be favoured by systems with short-term storage and frequent charge-discharge cycles, while lower conductivity is likely to be favoured in cases of longer-term storage. Realistically, the suitability of a site for BTES will be chosen based on low groundwater flow and whether there is proximal surface demand.

Little research has been undertaken on deep BHEs for BTES, although

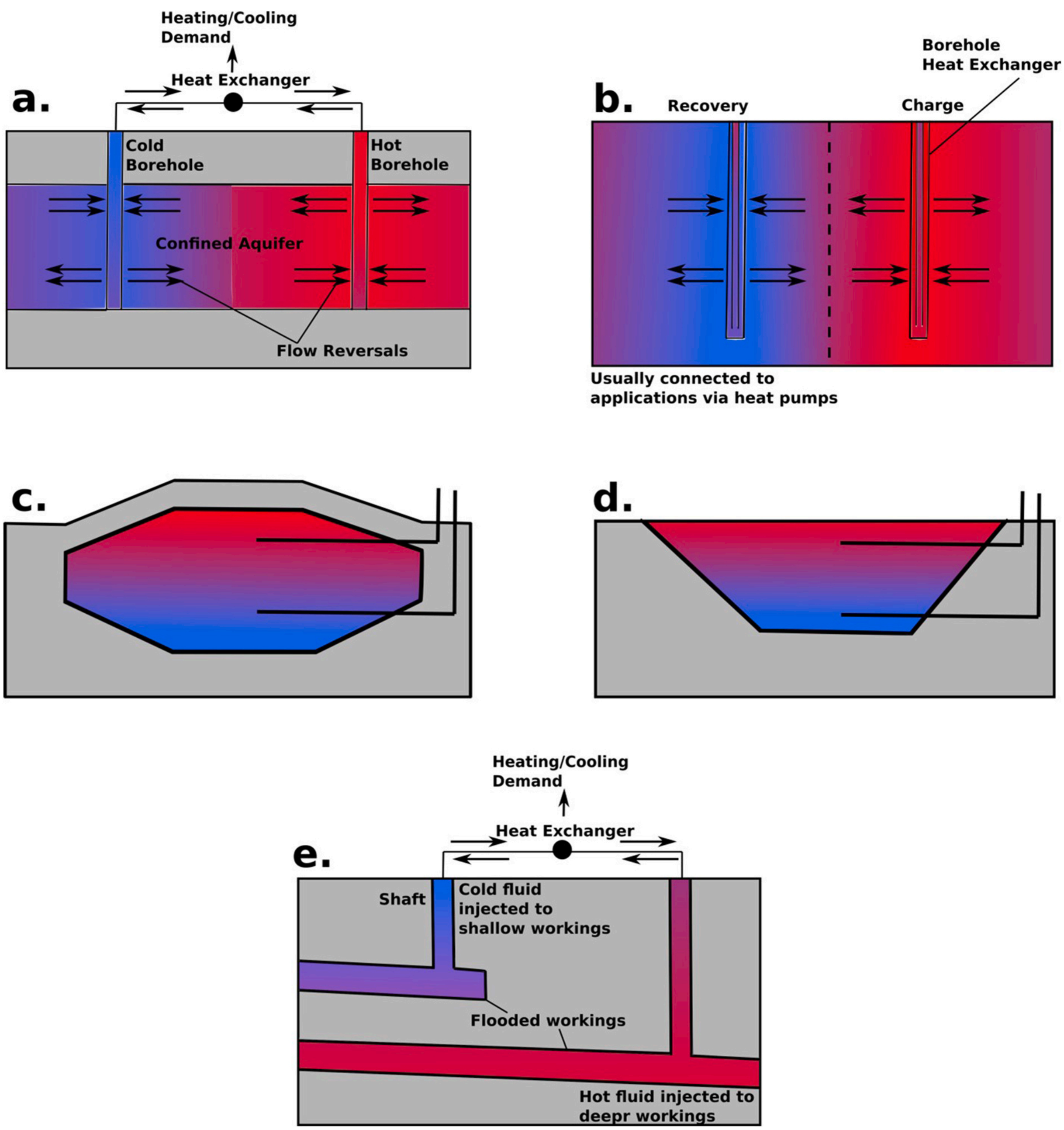

Fig. 1. Schematic of (a) aquifer thermal energy storage, (b) borehole thermal energy storage (coaxial pipe), (c) tank thermal energy storage, (d) pit thermal energy storage and (e) mine thermal energy storage. Note for BTES there would typically be an array and in the diagram the two boreholes are shown to highlight charge and recovery of heat which would occur at separate times (i.e., winter versus summer).

as deep BHE arrays tend to have a high exposed surface area to volume ratio, through which heat loss could occur, one would not expect them to be especially efficient. Some modelling studies have suggested that at medium depths (<1 km) groundwater flow affects the performance of BTES schemes [47]. For deep BHEs, due to the higher bottom-hole temperature caused by the geothermal gradient, higher temperature fluid must be circulated during a charging phase to ensure that heat is transferred to the rocks rather than extracted. Xie et al. [49] suggested there are optimal inlet temperatures for more efficient storage at different depths, but storage efficiency is generally low (typically <40 %) for deep single well BTES and the increase in thermal energy extracted in comparison to without storage is minimal [50,51]. This also applies to shallow single well BTES systems [52].

Closed-loop borehole installations in the UK have become increasingly popular since 2000, some of them serving large commercial buildings with heating demand in the winter and cooling demand in the summer [53]. These could thus be described as having similar character to BTES systems, although it is seldom the case that heat rejection and extraction are thermally balanced. For example, the ground source energy company ICAX has installed BHEs and BTES systems at Wellington Civic Centre, Suffolk One College, Merton's Acacia Intergenerational Centre and Greenfield Supermarket [54]. Other BHE schemes with heating and cooling loads exist, such as in Leicester which was dominated by cooling loads and heat rejection into the ground in the first years of operation [27]. Nevertheless, the current use and operation of BTES systems in the UK are limited; a 2016 study estimates domestic and non-domestic BTES numbers were in the 10s [53], although "BTES" was not rigorously defined as a concept. More UK BTES systems are planned, however (e.g., Ref. [55]). In the UK, there is no central register for closed-loop borehole schemes and no need to acquire a licence to construct or operate them; it is suspected that the BEIS document [53] underestimates the numbers of closed-loop BHE schemes incorporating elements of both heating and cooling.

A recent BTES installation is the Glasgow SWG3 "BODYHEAT" project (Fig. 2); this is aimed at capturing surplus heat from the cooling of a nightclub, introducing it to the ground via BHEs and recovering a proportion of it for use at times of peak heat demand. The site (NS 56263 65785) is underlain by unsaturated clays and gravels, followed by saturated bedrock, consisting of siltstone, sandstone and mudstone. The closed-loop array comprises 12 boreholes in an adjusted U-shape configuration, with no less than 8 m spacing between each borehole. The boreholes are drilled to 200 m depth at 115 mm diameter and installed with single 40 mm OD HDPE U-tube heat exchanger pipework grouted into the boreholes. A non-toxic, glycol-based carrier fluid has been carefully selected to optimise its frost protection characteristics and minimise the hydraulic resistance of the closed-loop array (ultimately to improve the efficiency of BODYHEAT). The heating and cooling are provided by two, twin-unit ground-coupled heat pumps with a total heating and cooling capacity of 123 kW, albeit with a potential for further load to be added in the future. The heat or coolth is currently provided to three separate spaces within the nightclub – a 1250-person capacity event space, 1000-person event space and the main foyer entrance. One of the heat pump units can provide simultaneous heating and cooling, allowing for instantaneous use of waste heat. The surplus heat is then captured and pumped into the borehole array for storage, to be used for heating later.

BODYHEAT has been constructed and commissioned and is fully operational (as of October 2022). The typical annual consumption is expected to be around 70 MWh of heating and 170 MWh of cooling delivered by fan coil units during its first years of operation, with heat transfer rates of ~50W/m. Flow, temperature and pressure instrumentation have been installed across the plant room and within the borehole array manifold to monitor the energy storage performance. The system, at present, is thus an example of a cooling dominated ground heat exchange scheme, with a significant waste heat recovery (BTES) component. However, future expansion has been considered and incorporated into the original design so there is scope for the scheme to add additional heating loads and consequently, create a more thermally balanced scheme in the future.

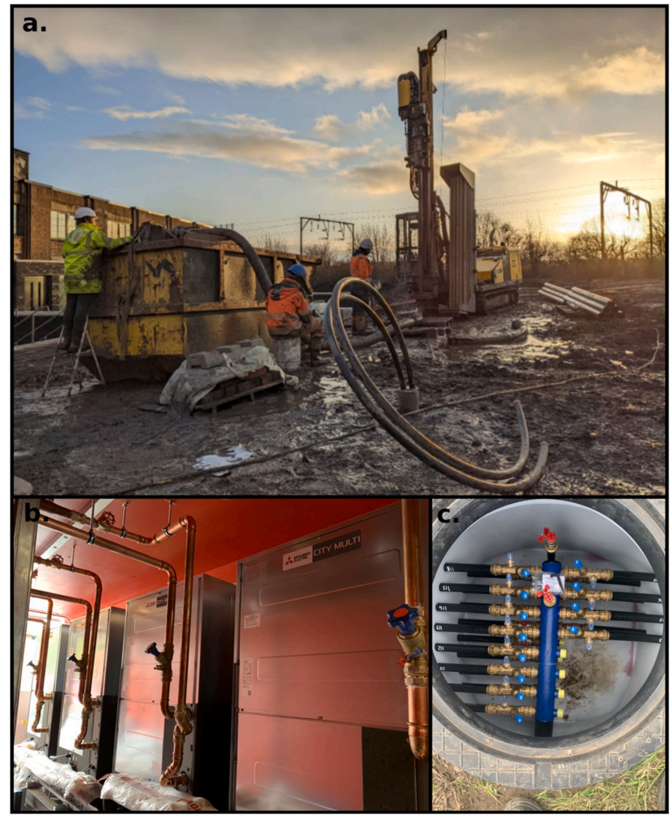

Fig. 2. Images from the Bodyheat project development in Glasgow: (a) drilling of the site, (b) two twin unit heat pumps – 4 total and (c) the manifold (pre-instrumentation).

2.2. *Aquifer thermal energy storage (ATES)*

ATES usually involves abstraction of groundwater, heat exchange, then reinjection into the natural rock, via a two well (doublet) or multi-well system (Fig. 1a). Heat is transferred to the subsurface rock through conduction and convection through one well which injects fluid and the other which produces fluid in an open-loop; these are usually then reversed depending on whether it is a charge or extraction period (e.g., Refs. [56–60]). In contrast to BTES, ATES requires specific geological conditions such as a natural aquifer with high hydraulic conductivity, preference for confining low permeability, low thermal conductivity layers, limited/no natural groundwater through-flow and suitable water chemistry [61]. Since initial heat transfer is dominantly by advection with groundwater flow through a large aquifer volume, ATES wells usually have a higher heat transfer capacity [62] than individual BTES boreholes, which rely predominantly on conduction within a limited rock volume. In addition to some of these key parameters in geological aquifer characterisation for ATES, modelling studies have also indicated that flow rate, injection temperature, well spacing and specific heat are equally important engineering parameters [53,63–66]. It is probable that shallow systems are more suited to ambient thermal storage and deeper aquifers to high temperature storage. This is due to thermal losses driven by the contrast between the stored heat and subsurface.

There are also further considerations with ATES systems, such as: 1) surface components (heat exchangers) - to prevent scaling from the geothermal fluid (e.g., Ref. [67]), 2) when thermally spent water is re-injected, there is a risk of mineral precipitation or biofilm growth, clogging by fine particles or bubbles of gas, and possible rearrangement of aquifer particles [4,68], 3) there is a reduction in storage efficiency (see Section 2.5) with increasing grades of heat stored (i.e., in high temperature systems heat losses are increased) [69] and (4) there may be some risk of ground movement if drawdowns or reinjection heads are excessive.

In contrast to some areas of Europe, such as the Netherlands, ATES is still an emerging market in the UK with few installations to date (<10 for non-domestic applications as of 2016 [53]). Some installations include the National Maritime Museum (London) and Westway Beacons (London) [53]. Early work by Adams [70] regarded the Cretaceous Lower Greensand and the Permo-Triassic Sherwood Sandstone as the most suitable aquifers for ATES in the UK. One of the earliest attempt at ATES in the UK was a trial carried out by the Institute of Geological Sciences (IGS) in the Lower Greensand aquifer at Reach, Cambridgeshire (Grid reference TL 559,658, [71]). The IGS research site comprised of four wells (well index number TL56/98), one active well (6″ PE liner within 8″ borehole) and three observation wells (4″ PE liner within 6" borehole) with slotted screen in the Lower Greensand sections. The Lower Greensand top was ~35 m deep, and ~13 m thick. It comprised of unconsolidated clayey-fine sand, between Cretaceous Gault Clay and Jurassic Clay. The transmissivity of the aquifer was estimated at 50–70 m^2/d. Hot water was generated by propane burners in the field. Over 77 days, 1520 m^3 of hot water, representing 86.6 MWh heat, was injected at a mean temperature of 57 °C and an average rate of 0.23 L/s. There followed a storage period (no pumping) of 105 days and an abstraction period of 97 days when water was recovered at an average rate of 0.23 L/s. The abstracted water temperature fell over this period from c.32 °C to c.18 °C. Around 28.2 MWh of heat were recovered, a recovery rate of c.32 %. The low rate of heat recovery was ascribed to the low volume of water injected during the trial and to the thin nature of the aquifer (higher conductive heat loss).

2.3. Minewater thermal energy storage (MTES)

Flooded mines (or caverns) can be used for thermal energy storage. MTES systems have a significant potential for energy generation and storage (e.g., Ref. [72]). Mine shafts are widespread throughout the UK, with voids left after mining usually flooded with rising groundwater when pumps are turned off on mine closure. They can, therefore, provide a significant geothermal resource; Rodriguez Diez and Diaz-Aguado [73] have estimated that 3000MW_{th} could be produced from flooded mines within Europe. MTES systems operate in a similar manor to ATES systems with two or more wells injecting and extracting hot/cold fluid into a flooded mine (Fig. 1e); however, it may be more optimal to inject/extract hot/cold into workings at different depth (e.g., such as in Heerlen, Netherlands [74]). They are an option for UTES as they have a relatively stable temperature but are likely to require a heat pump for operation [30]. Furthermore, the increased hydraulic conductivity and behaviour within the mine roadways or voids in contrast to other technologies can allow high yields (pumping rates) to be achieved [75]. Mines which are naturally fully flooded (i.e., have little-to-no air within), have surface areas equal to or greater than 1 Ha, are fully sealed are sought after to allow storage temperatures to trend asymptotically to the injection temperature [76] and should have minimal through-flow. Storage efficiency may be lower than other types of UTES technology [77]; however, it is worth noting the study neglected local advective transport and acknowledged multi-well systems could improve the recovery of stored heat.

Current research projects aim to de-risk minewater geothermal operation in the UK (e.g., Ref. [78]), but few commercial systems are in operation. The UK Government has provided funding for a mine water geothermal heat network at Seaham Garden Village [79], whilst other projects are already exploiting the warm waters of flooded mines (Gateshead) (e.g., Ref. [32]). It is not believed that any MTES component will be incorporated into these schemes in the immediate future, however.

2.4. Tank thermal energy storage (TTES) and pit thermal energy storage (PTES)

TTES systems use a thermally insulated, reinforced concrete/steel, storage tank buried underground to limit heat loss [61] (Fig. 1c). PTES systems operate by sealing water and/or gravel pits in the shallow subsurface with a clay and rubber membrane plus floating lid (Fig. 1d) [3]. It has been found that TTES and PTES: 1) are less influenced by geological conditions than ATES/BTES, but require higher construction costs, 2) provide greater charging than ATES/BTES and 3) PTES tend to decline in performance as depth decreases and therefore, TTES becomes more efficient [80,81]. It has also been suggested that PTES is more reliable than other storage methods [82]. TTES and PTES usually store higher temperature fluid (up to 100 °C) and are therefore, commonly used for district heat networks [83,84]. In the UK, TTES use is widespread in all applications (but largely above ground), from domestic sector (within 11 million homes) to district heat networks, whilst PTES has one project identified in the UK [53]. Both TTES and PTES also require a greater surface land footprint, which may make them unattractive for large scale UTES in densely populated areas within the UK.

2.5. Comparison of UTES storage efficiencies

A variety of UTES methods have been considered in the literature using modelling studies, feasibility analyses and case studies. Storage efficiency (*SE*) is often determined as the ratio of energy extracted to injected (e.g., Refs. [85,86]):

$$SE = \frac{Total\ Energy\ Recoverd}{Total\ Energy\ Injected} \tag{1}$$

This can be a particularly useful metric within higher temperature shallow systems; however, it does not consider the energy that would be extracted (e.g., from a BHE array) under normal conditions without charge. Therefore, it can produce misleadingly high apparent efficiencies exceeding 100 %. Studies have suggested there are better metrics for analysing the storage efficiency, where the increase in energy recovered in contrast to the same system without thermal recharge was considered [50,51].

Efficiency varies between each storage method and BTES appears to be the least efficient method (Table 1). Although BTES appears to be the poorest storage technology in terms of efficiency, it does however, have a reduced cost in comparison to others and its storage efficiency increases with time [87]. It can take up to 5 years for higher temperature BTES systems to reach their optimal storage efficiencies [4]. This does; however, only apply to BTES systems where temperature is being charged significantly above ambient conditions. The efficiency of BTES systems increase with array size and equal-dimensions and with ground surface insulation. Therefore, when considering a UTES technology, other factors in addition to efficiency must be considered, such as the subsurface geology, initial capital expenditure and scale of STES system. It is also worth noting the efficiencies listed in Table 1 are dependent on the operating mode and storage consisting of shorter durations may have higher efficiency as more energy can be recovered as there is less time for lateral thermal propagation. While out of the scope of this study, due to their considerable variability, energy capital costs are listed in Table 1, but for further analysis see Ref. [88].

3. Geospatial and geological suitability for BTES, ATES and MTES systems

3.1. BTES

As previously outlined in Section 2.1, the critical geological parameters for BTES systems are no/low groundwater flow (e.g., Ref. [47]) and high ground volumetric heat capacities. Thermal conductivities can also be important to minimise radial propagation, or to enhance transmission

Table 1
Summary of storage methods considered and their respective efficiencies (Eq. (1)). After [36,53,88–92].

Type of UTES	Description	System Efficiency (typical for seasonal operation)	Operating Temperature (°C)	Heat Storage Capacity (kWh/m^3)	Energy Capital Cost (€/kWh)
Borehole thermal energy storage (BTES)	Vertical BHEs are drilled into the ground and typically used in arrays at shallow intervals. Heat is exchanged from the circulating fluid across the borehole/rock interface (via pipework, casing or backfill).	6–61 %	0–90	15–30	0.41–0.8
Aquifer thermal energy storage (ATES)	Usually comprises of an open-loop multi well system that injects and circulates fluid through the natural rock via advection.	Up to 80 %	Low (5–30) Medium (30–60) High (>60)	30–40	[a]
Tank thermal energy storage (TTES)	Water or oil is stored within a tank.	50–90 %	<100	60–80	0.69–5.55
Pit thermal energy storage (PTES)	Use shallow pits dug into the ground filled with gravel and/or water. Heat is then either transferred directly to this medium or by plastic pipes running through the ground.	<80 %	<95	30–80	0.46–2.91

[a] Energy Capital cost not provided due to the strong variability.

of heat into the rock in short charge periods. Areas of higher thermal conductivity rocks (>3W/(m·°C)) in the UK are constrained to quartz-rich sandstones and granites (e.g., Refs. [9,10,93–96]). The granitic rocks typically exceed depths of BTES operation (i.e., >300 m) or outcrop in areas of low population density. Therefore, they are unlikely to be suitable for BTES. Although if granites occur in the shallow subsurface they may be suitable and there is the option to leave the well-completion as 'open-hole' for high rock strengths, which can lower drilling costs. Additionally, engineering parameters (such as array design, period of charge etc.) may be the most important factors in dictating the viability of any development. When considering the method of UTES it may be a case of identifying areas where ATES/MTES is less suited based on subsurface conditions (i.e., see closed-loop v open-loop system suitability in Fig. 3).

In the UK, several lithologies are recognised to have rock properties that inhibit groundwater flow (i.e., permeability). In this section, the outcrop and near surface subcrop are considered with typical BTES arrays running to a few hundred meters depth [92]. There are multiple thermally insulating major shales and clay/mudstone units in the UK covering widespread geographical areas; including, but not limited to the Mercia Mudstone Group, Jurassic Lias, Oxford Clay, Bowland Group, Craven Group and Kimmeridge Clay Formation. Modelling studies have shown that hydraulic conductivity and Darcy velocity of rocks should be less than 1e-7 m/s [107–113] respectively, to minimise thermal

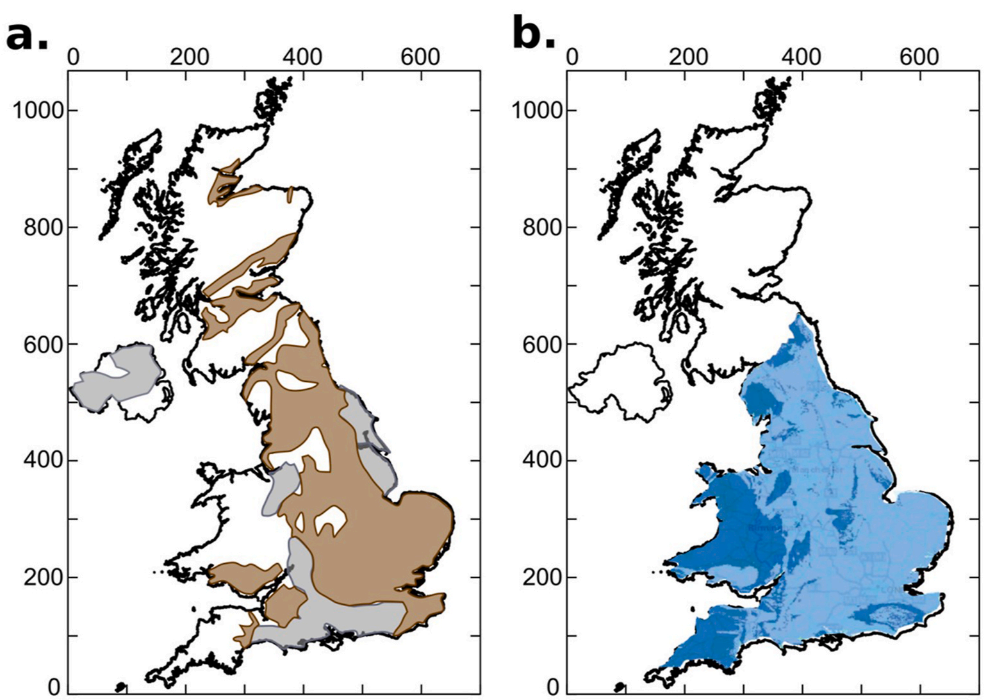

Fig. 3. (a) Geospatial distribution of aquifers in the UK (after [5,37,97–101]). Brown represents the presence of aquifers (unconfined, concealed or confined) across the UK, whilst grey represents the major, deep (potentially geothermal) Permo-Triassic Basins. These areas could be considered for ATES systems, whilst the Permo-Triassic basins may be considered for shallow to deep storage. Modified using BGS data: Contains British Geological Survey materials Copyright NERC 2022. British National Grid coordinates (north and east) are in 100 km intervals. © Crown copyright and database rights 2022 Ordnance Survey (100025252). (b) Map highlighting ground source heat pump selection tool in England and Wales (modified from Ref. [19]). Light blue indicates open-loop suited systems, whilst dark blue indicates closed-loop suited systems. Contains British Geological Survey material © UKRI 2012; contains Environment Agency data © Environment Agency copyright and database right; contains Ordnance Survey data © Crown copyright and database right 2012. The GSHP Screening Tool map was created using ArcGIS® software by Esri and contains the 'World Topographic' and 'World Imagery' basemaps used herein under licence. Copyright © Esri. All rights reserved. For specific outcrop localities of shale, see Refs. [102,103,104,105]. For outcrop localities of the Mercia Mudstone Group, see BGS [106].

propagation of the thermal plume away from the BHE array, which consequently negatively impacts the efficiency of the system (e.g., Ref. [114]). Therefore, it is likely BTES systems can operate across much of the UK.

A thermally inhibiting unit with moderate volumetric heat capacity and low permeability in the UK is the Mercia Mudstone Group (MMG). This outcrops widely across much of the UK with a northeast to southwest trend and further outcrops around the Cheshire, Lancashire and Carlisle Basins. In literature, thermal conductivity ranges from 2.28 ± 0.33W/(m·°C) [115] to 1.88 ± 0.03W/(m·°C) [16]. Further work from Banks et al. [93] measured the thermal conductivity to be 1.49–2.58W/(m·°C) from thermal response tests which assess the horizontal conductivity based on the radial nature of the tests around a BHE. Further analysis has been undertaken which suggests that the thermal conductivity in the MMG is more responsive to local lithology with a far higher range of 1.67–3.24W/(m·°C) [102]. The higher values are based on thermal conductivities in sandstone with high-quartz content. There are further issues to consider with the MMG, such as subsidence, swelling and ground movement caused by dissolution of evaporites [116]. Therefore, the local geology must still be considered during feasibility studies.

The Jurassic Lias, Oxford Clay and Kimmeridge Clay Formations outcrop in a similar northeast to southwest trend to the MMG, with similar thermal characteristics, dipping east and consists of mudstones and limestones [103]. Thermal conductivity values are in the order of 1.8 ± 1.1, 1.57 ± 0.03 and 1.51 ± 0.09W/(m·°C), respectively [115]. There are also additional minor localised shale outcrops in South Wales and North England (Marros, Bownland and Craven Groups).

Other areas which will have limited groundwater flow include central to northern Wales, northern England, southwest England and much of Scotland. This is due to the presence of metamorphic and igneous rocks, which usually have low primary porosity and permeability. Typically, granitic zones have higher heat flow, thermal conductivities, and radiogenic heat production; therefore, these could prove suitable BTES systems operating with higher grade heat or shorter charge periods. A key issue is the granitic localities in the UK which are typically not within the shallow subsurface (e.g., Refs. [10,117]). However, where the metamorphic and granitic rocks outcrop, such as the Grampian Highlands (e.g., Dalradian and Moinian Supergroups) (e.g., Refs. [118–120]), Caledonian geology could be suitable with open-hole completion similar to that in Scandinavian countries (e.g., Refs. [121,122]). Granitic and metamorphic rocks also do not have the geotechnical risks (i.e., subsidence, swelling, dissolution) associated to mudstones/clays.

It is also worth noting that the location of populous regions may determine the necessity for thermal energy storage more so than optimal geological characteristics. Therefore, for any localised feasibility studies for BTES systems array design, spacing, operational pattern (i.e., full-load hours), heat sources, operating temperature and heat pump efficiency may also determine the potential for BTES systems (e.g., Refs. [52,123]). In this section we have focused on bedrock in the UK for BTES, but it is also important to consider the superficial deposits, which will also play an important role in shallow systems. Several tools exist to investigate the shallow (<10 m) potential for ground source heat pumps, which map the thermal conductivity and suitability for installing such systems [124].

3.2. ATES

There are 6 major aquifers in the UK which can be considered for ATES: Cretaceous Chalk, Cretaceous Lower Greensand, Jurassic Limestone, Permo-Triassic sandstones, Permian Magnesian Limestone and Carboniferous Limestone [125]. These underlie large areas of England and smaller localities in Wales, Scotland and Ireland, either as unconfined or confined aquifers. They have proven hydraulic characteristics suitable for abstraction which are well constrained in Allen et al. [125], with a detailed focus on the hydrogeology. The spatial distribution can be identified in Fig. 3. Low thermal conductivities in over-and underlying beds may be advantageous in limiting vertical thermal propagation, and lack of natural groundwater through-flow will minimise advective heat losses. Both these factors should increase storage efficiency and subsequent recovery.

The Cretaceous Chalk is in the south and east of England, its hydrogeology is characterised by the presence of dual porosity systems enhanced by fractures and dissolution, creating groundwater conduits or karstic features (e.g., Ref. [126]). This means that effective porosities can be low (<1 %) and transmissivities very high. There is a risk that, when injecting heat or coolth into the aquifer, heat transfer is limited to a few fracture conduits rather than the entire aquifer thickness. Moreover, high hydraulic gradients in some areas, coupled with high transmissivities, can lead to extremely rapid groundwater flows, with the potential to "advect away" stored heat. MacDonald and Allen [127] analysed a large proportion of data from the UK, suggesting this to be a potential key aquifer for groundwater based on the high-quality hydraulic properties (i.e., high permeability and porosity); however, they did acknowledge the data was biased with testing being conducted in valleys where the yield is highest. The study highlighted that when confined, the transmissivity of the aquifer reduced by a factor of 4–5 in contrast to unconfined conditions due to the highly compressible nature of the Chalk and lack of fracture dissolution by active groundwater flow, especially during periglacial times [128]. Furthermore, there could also be difficulty in predicting fracture porosity (e.g., Ref. [129]), which could limit connectivity between wells. The Jurassic, Permian and Carboniferous limestones are widespread across much of the UK and, similarly to the Chalk, have low primary (matrix) porosity-permeability relationships, but typically have high secondary, fracture (or karstic) porosity [130–132]. This is likely to pose similar issues to the Chalk for UTES, such as limited connectivity between wells, or in contrast, rapid thermal perturbations between wells associated to high transmissivities in conduits, and difficulties in predicting fractures. Therefore, these lithologies are unlikely to be suited for ATES unless there are low hydraulic gradients, high porosity, high permeability and long charging cycles to conduct heat into the bedrock.

The Lower Greensand is exploited in the southeast of England and is a prominent groundwater supply where the Cretaceous Chalk is absent [133], forming the second most important aquifer in the London Basin [134]. There are significant areas of confined aquifer in proximity to high population densities, such as Luton, Slough and Guildford [135]. Furthermore, ATES testing into the aquifer has been undertaken (Section 2.2 [71]). While storage efficiency was low (c.32 %) it was anticipated that with continued STES efficiency could reach 66 % [136].

The Permo-Triassic Sandstones are geographically widespread and exploited for groundwater. They have also been highlighted as a prospective target for ATES due to their high intergranular flow, low clay content and significant thicknesses which lends them to large-scale operation [70]. Aquifers are located at outcrop to depths of ~4.5 km across much of England and Ireland. They supply ~25 % of groundwater abstractions in England and Wales, with yields up to 10,000m^3/day [137]. Aeolian to fluvial deposits create anisotropy with Permo-Triassic aquifers through layered fine-scale laminations of clay, but studies on hydraulic characteristics have recorded the median values of core porosity to be 26 % and hydraulic conductivity of 0.56 m/day [125]. It is worth noting the range of porosity recorded for the previous study was 2–35 % and hydraulic conductivity data varied over 6 orders of magnitude.

Deep Permo-Triassic aquifers are largely concentrated to seven major Mesozoic basins in the UK. It has been estimated that these have the most suitable hydro-thermal characteristics for geothermal exploitation and a combined low-enthalpy resource of 327×10^{18} J [5,9,98,138,139]. It is reasonable to assume that the aquifers would be favourable for ATES; however, it may mean that at increasing depth, they require higher charge temperatures. Major basins share synchronous Permo-Triassic aquifers with similar properties for the Triassic Sherwood Sandstone Group (SSG) and Permian sandstones (Table 2). In ATES it is essential for high-quality hydraulic characteristics to ensure that fluid can be injected into the aquifer without high pressure build up.

The Triassic SSG is currently in use for the geothermal system coupled to the district heat network at Southampton in the Wessex Basin (e.g., Refs. [140–142]). Interestingly, the Marchwood exploration and Western Esplanade development wells identified high transmissivities, flow rates and aquifer thicknesses of ~60 m [6]. They are also within a few kilometres of each other, have laterally connected aquifers and already have suitable surface infrastructure [140,143,144]. It could therefore be hypothesised that this could prove a useful place to test a deep doublet ATES system in the UK. The only potential issues could be the high salinities observed (<300 g/L), which can vary significantly in a few kilometres [5]. This may cause issues during recovery as density driven flows can increase thermal propagation, leading to poor thermal storage.

There are also other potential aquifers in the Wessex Basin; but research has shown that they are likely to be heavily indurated with poor porosity and permeability (Old Red Sandstone, Devonian); however, they may have high secondary permeability in fractures [145,146]. There are also Permian rocks which typically yield low-moderate flow rates (<5 L/s) and lie to the west of the Wessex Basin [125].

3.3. Repurposing of oil wells

The concept of repurposing existing onshore hydrocarbon wells for geothermal utilisation in the UK has been investigated by several authors, highlighting significant scope for development [17,147–151]. Several have investigated the potential for repurposing such wells as geothermal using open-loop systems (e.g., [17]) while other have considered closed-loop deep BHE systems [152–157]. After a duration of use, if this technology is no longer economic, then the infrastructure might be repurposed for STES (i.e., ATES or BTES) [148,152].

Prior to March 2022, the UK regulator, the North Sea Transition Authority (NSTA), required that wells are abandoned following the cessation of hydrocarbon exploration or production, preventing their reuse for geothermal purposes. However, (as of 31/3/2022) the NSTA temporarily suspended this decommissioning requirement for three wells at the Elswick and Preston New Road sites to allow operators to evaluate reuse options [158]. In anticipation of further announcements such as this in the future, and the assumption that necessary regulatory changes will be adopted which recognise the added value of repurposing, a re-assessment of candidate onshore wells suitable for repurposing for UTES is warranted.

Following the approach of Watson et al. [17,159], an assessment of the NSTA's Onshore Well Database and Marine Scotland's Onshore Oil and Gas Well Interactive Map was carried out to determine candidate onshore wells suitable for repurposing for UTES based on the well operational status. The NSTA classify wells as: drilling, completed (operating), completed (shut in), plugged, or in abandonment phase 1, 2, or 3 [160]. The NSTA Onshore Well Database contains data relating to onshore wells drilled in England. For the purpose of this assessment, onshore well data for Wales and Northern Ireland were taken from Watson et al. [17,159]. The Marine Scotland Interactive Map contains wells which have been completed and are unplugged. Those wells of most relevance to the present study are those which are currently operational, and are thus future candidates for repurposing, and those which are presently approaching cessation of hydrocarbon production but have yet to be plugged, for which repurposing would delay the onset of decommissioning operations and prolong the life of the well.

Of the 2244 existing onshore hydrocarbon wells in the UK, Table 3 shows that in England there are 329 wells which are 'currently operational', and 120 wells which are 'shut-in', and in Scotland there are 15 wells which are 'unplugged'. These wells are deemed to be the most favourable for repurposing for UTES and could be considered for further site-specific examination, including an assessment of the well structure, well integrity, proximity to local heat end-users, and proximity to waste heat resources. The location of each of these candidate wells is shown on Fig. 4, with those fields with the largest quantity of candidate wells highlighted, such as Wytch Farm, Welton, Beckingham, Gainsborough, and Doe Green.

This shows there is potential in repurposing wells within the UK for geothermal development. Issues remain, such as, high charge temperatures are required due to the higher average ground temperature and this would reduce storage efficiency in such systems (although this can be improved with shorter charge periods) [49–51]. Therefore, these systems should be used with shorter periods of charge to improve storage efficiency and should be only considered an option if there are no other suitable more efficient methods of thermal energy storage. Finally, there is potential for contamination from hydrocarbons or geochemically problematic brines in open-loop ATES systems which may limit development.

3.4. Repurposing of abandoned mines for MTES

Another legacy energy asset which could be utilised for thermal energy storage in the UK are abandoned mine workings. The Coal Authority estimates that there are 23,000 abandoned deep coal mines around the UK [37], and that approximately 25 % of the UK's housing and businesses are located above former coalfields [163]. There is, therefore, an opportunity to utilise abandoned mine workings for the

Table 3
Status of UK onshore hydrocarbon wells. Data from Refs. [17,161,162].

Operational Status	Number of Wells
England, Wales & Northern Ireland	
Completed (Operating)	329
Completed (Shut-In)	120
Drilling	1
Plugged	23
Abandonment Phase 1	225
Abandonment Phase 2	58
Abandonment Phase 3	1369
Scotland	
Unplugged	15
Plugged/Abandoned	104
Total	2244

Table 2
Hydraulic conductivities (m/d) of Permo-Triassic aquifers. Information on core data collated from Allen et al. [125], note likely collected at shallow depths.

Basin	Age	Stratigraphy	Min	Max	Geometric Mean	Interquartile Range
Cheshire	Triassic	SSG	3.70×10^{-5}	15	0.26	0.08–1.5
	Permian	Collyhurst Sandstone Formation	3.70×10^{-5}	10	0.4	0.13–1.8
Wessex	Triassic	SSG	1.00×10^{-5}	6	0.011	3.9×10^{-4} - 0.31
Worcester	Triassic	SSG	4.60×10^{-6}	17.8	0.5,0.37,0.49[a]	0.28–2.1,0.12–1.58,0.18–3.5[a]
	Permian	Bridgenorth Sandstone Formation	2.50×10^{-4}	9.4	0.49	1.1–4.01
East England	Triassic	SSG	1.90×10^{-6}	20.5	0.39	0.14–2.12

[a] For each respective formation from the Bromsgrove, Wildmoor and Kidderminster respectively. SSG = Sherwood Sandstone Group.

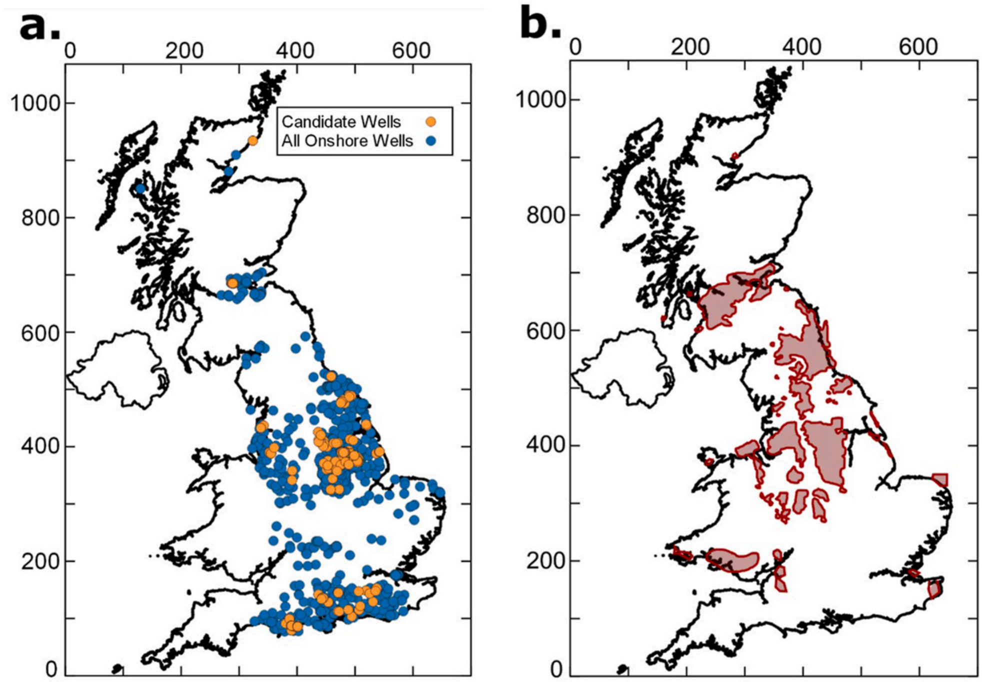

Fig. 4. (a) Map of the UK highlighting existing oil and gas wells with potential for repurposing (modified and updated after [17]), (b) red polygons on map of the UK highlighting coal mines (modified from Ref. [37]). British National Grid coordinates (north and east) are in 100 km intervals. © Crown copyright and database rights 2022 Ordnance Survey (100025252).

generation of renewable heating and for MTES, in areas of dense urban population and high heat demand [37,164–166]. While there have been limited studies on MTES in the UK, there is potential for future MTES testing in the UK geoenergy observatory in Glasgow, where multiple boreholes are drilled at the Cuningar Loop [167].

4. Comparison of thermal capacity of different UTES technologies

The work by Gluyas et al. [37] estimated the capacity for UTES of abandoned mines, potable aquifers and deep saline aquifers (Fig. 5). The highly theoretical total storage capacity of aquifers and mines ranges from 16.6 EJ to 166 EJ assuming temperature increases of 1 °C and 10 °C, respectively [37]. In some cases, it is possible that the increase in temperature of the subsurface could be greater than 10 °C – particularly if considering a medium-to high-temperature heat source for the charge period (e.g., Refs. [56,168,169]). In this study, the estimate was extended to include a temperature difference of 15 °C. This subsequently increases the higher end capacity from 166 EJ to 250 EJ. There are several issues with this approach: 1) heat transfer for storage within the subsurface is for fluid only; however, realistically, the volume of adjacent rock mass for ATES would also contribute to storage, 2) there may be limitations preventing the increase in temperature within the aquifers past ambient levels (i.e., due to future and existing government restrictions) and 3) it does not consider the hydraulic nature of the aquifer (i.e., permeability and porosity). Therefore, the useable national storage capacity is likely to be orders of magnitude less and dependent on local conditions.

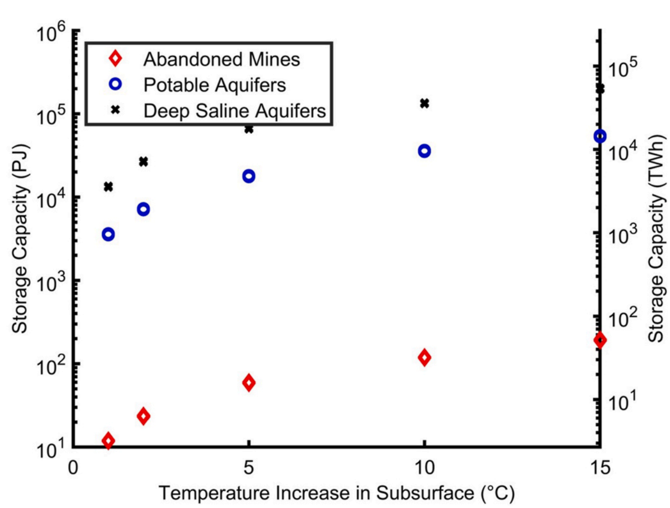

Fig. 5. Storage capacity for ATES and MTES systems (after [37]) with increasing in temperature difference. Note 1 Petajoule (PJ) = 10e15 J (J).

Initial attempts have been made to quantify the storage potential for ATES and MTES, whilst the storage potential for BTES has not been quantified in previous literature. In this study, a different approach was chosen in contrast to the wider storage capacities for the UK by Gluyas et al. [37]. The storage capacity for a notional range of volumes which correspond to those used in the subsurface by BTES systems were calculated. They can be utilised specifically for UK BTES, or internationally to calculate the size of the array required once demand/charge is known. These were calculated for the volumetric range of 20^3 m^3–150^3 m^3 and temperature increases typical of shallow BTES schemes (1–15 °C (e.g., Ref. [170])). The volumes were equidimensional (i.e., for 20^3 m^3 the dimensions were set as 20 × 20 × 20 m) and the volumetric heat capacity set as 2.2MJ/(K·m^3) which is typical for the UK. The storage capacity for a 20^3 m^3 volume ranged from 17.6 to 264 GJ, whilst for a 150^3 m^3 volume, the range was 7.4 to 111 TJ (Fig. 6).

5. Heat sources and sinks

5.1. Heat demand

In the UK, heat-use correlates to ~50 % of the total energy demand [171] and decarbonisation of the sector is integral to contributing to the national net zero carbon emissions targets by 2050 [172].

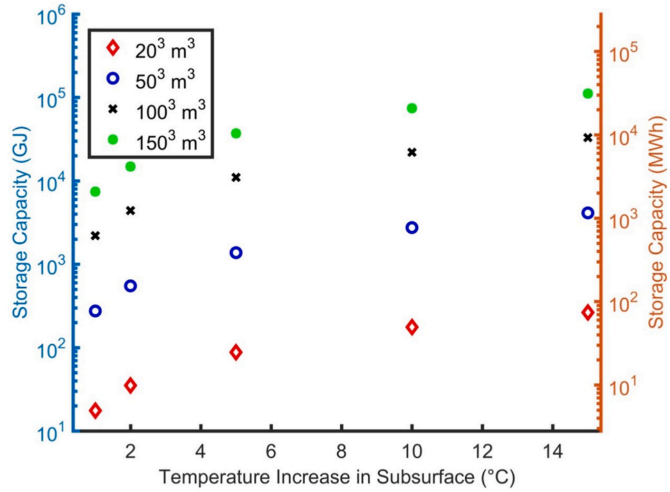

Fig. 6. Storage capacity for borehole thermal energy storage systems with varying volumes and increase in temperature difference. Note 1 Gigajoule (GJ) = 10e9 Joules (J).

Unfortunately, inefficient transport of heat, in contrast to fuels, means population density and heat demand may dictate operation of any thermal energy storage scheme. Significant demand remains concentrated in areas of high population density with an annual demand of 463 TWh for heating and 39 TWh for cooling [1]. Large proportions of heat demand coincide with aquifers and mines [37], whilst the majority of waste heat is produced in populated areas. Major cities in the UK, such as Bristol, London, Birmingham and Manchester have the most demand (e.g., Refs. [9,142]), reaching in excess of 38 GWh/km^2/year (Fig. 7). Similarly, the greatest cooling demand is concentrated in cities but in far lower quantities (Fig. 8).

Locations of high population density are underpinned by regional aquifers and/or mines. Therefore, based on demand and supply, both ATES and MTES systems may be most suitable. There is, however, a requirement to consider the surficial spatial requirements of such systems and whether in densely populated areas, these will be possible. Based on the spatial requirements, large scale PTES and TTES systems are likely to consume too much surficial space in populous areas.

5.2. Waste heat

All industrial heating processes produce surplus heat. In some circumstances, the surplus heat may be recovered and reused by increasing the efficiency of the process itself or by meeting an external heat energy need. If surplus heat is not recovered, then it will be lost to the environment and wasted. The potential for recovery and reuse is determined by the grade and location of the heat source. The grade of waste heat is a function of temperature, where higher temperatures have a higher grade. High grade recoverable heat is greater than 300 °C, medium grade is between 100 °C and 300 °C and low grade is below 100 °C [173]. Waste heat at higher grades allows for more efficient recovery but low-grade heat is the most abundant. The heat grade determines the potential uses and the location determines the potential consumers with economic factors adding further constraints.

There are significant quantities of waste heat emitted by industry in the UK. In 2008, the UK Government Office of Climate Change found that there was 65PJ per annum of waste heat with recovery potential in the UK [174]. There is also likely to be significantly more waste heat from space cooling and air conditioning which could add to this total and would appear ideal for UTES. McKenna and Norman [175] used data from the EU Emissions Trading Scheme to build a spatial understanding of waste heat potential by considering the largest industrial sites covering 60 % of industry. Their finding was that there is a technical potential for between 36 and 71PJ of recoverable waste heat with the iron and steel, chemicals, cement and glass sectors having 80 % of the potential recoverable heat. Further work considering the recovery technologies found that there is a potential for 52PJ of recoverable heat [176] where greatest potential was found for on-site reuse or conversion into electricity. Albert et al. [34] carried out a spatial analysis of waste heat in the UK finding that total waste heat in the UK is 1404PJ per annum. This figure is significantly larger than other estimates due to the authors considering a wider range of data sources than previous researchers, the addition of waste heat from power generation, and through not considering what is technically possible to recover. Of the total waste heat available, 165.6 PJ was found to be from industry while the remainder was from power generation. The latter of which is likely to decline with time with the increase in renewable generation.

Hammond and Norman [176] found that a large proportion of surplus industrial heat is in low and medium grades (30PJ) which have low potential for on-site reuse due to low demand in these grades. Low and medium grade waste heat is useful however in district heating networks. 4th generation district heating networks [177] in particular have the potential to recycle low and medium temperature waste heat through enabling a supply temperature of between 30 and 70 °C. District heating could therefore, unlock a significant low temperature heat demand not considered in the analysis of previous authors.

To integrate low and medium grade waste heat with UK heating demand through district heating networks requires the producers and consumers of waste heat to be in close proximity (several km). Albert et al. [34] showed that waste heat is concentrated in parts of the UK with high population density which could enable the efficient reuse of heat. This pattern is illustrated in Fig. 9, which shows around 1500 waste heat sites and the population distribution.

As a significant proportion of heating demand in a district heating network will be in winter in the UK, STES will be required to allow waste heat sources to contribute to meeting heat demand. Gluyas et al. [37] showed a correspondence between UK population density and potential STES sites which, combined with the proximity to waste heat sources, would open a significant number of new consumers for waste heat.

5.3. Solar power, wind curtailment and application to seasonal thermal energy storage

Solar energy is a key resource for the decarbonisation of heat in the UK. Global solar irradiation on a horizontal surface is approximately 1000 kWh/m^2 per annum across the UK (Fig. 10). However, this varies from 800 kWh/m^2 in the North of Scotland to 1200 kWh/m^2 per annum in the South of England [180]. Solar thermal technology can use this solar irradiance energy to deliver hot water, with a 3 m^2 panel being able to deliver half of the hot water demand for the average European household [181]. Gluyas et al. [37] estimated that 1000 km^2 of solar thermal panels on roofs and the ground could capture a similar amount of heat to their estimation of the total heat demand of the UK [142]. Despite these potentials, very little solar thermal has been employed in the UK for district heating, whereas successful case studies exist in Denmark [182]. Harvesting solar thermal heat for seasonal subsurface storage has the advantage that it is already in the form of waterborne thermal energy that can be injected into the ground (via a heat exchanger) without conversion and without excessive loss of exergy.

Since 2006, Britain has increased its wind generation from 50 TWh to more than 400 TWh in 2016 [184]. Consequently, in the same span of time, the volume of curtailed energy has increased from 0.13 to 3.53 TWh across the UK (Fig. 11) [184]. This is particularly prevalent in Scotland, where an abundance of generation capacity combined with network constraints gives an average curtailment rate of around 10 % for all onshore wind farms between the years 2015–2016 [184]. Additional wind farms are being built indicating that the amount of curtailed power due to network constraints is likely to increase significantly, despite the additional high-voltage direct current lines between

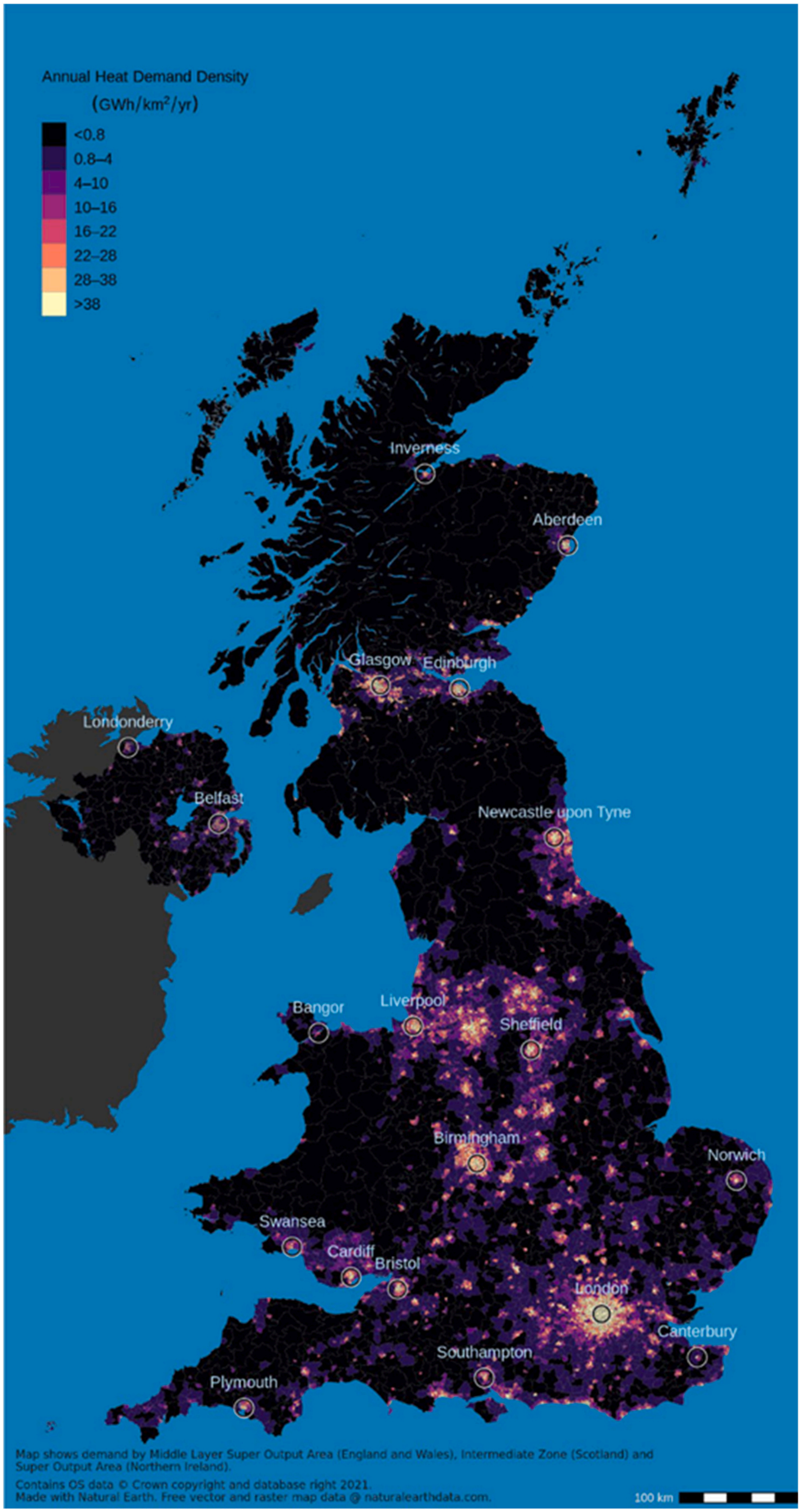

Fig. 7. Heat demand density in the UK (taken from Ref. [1]).

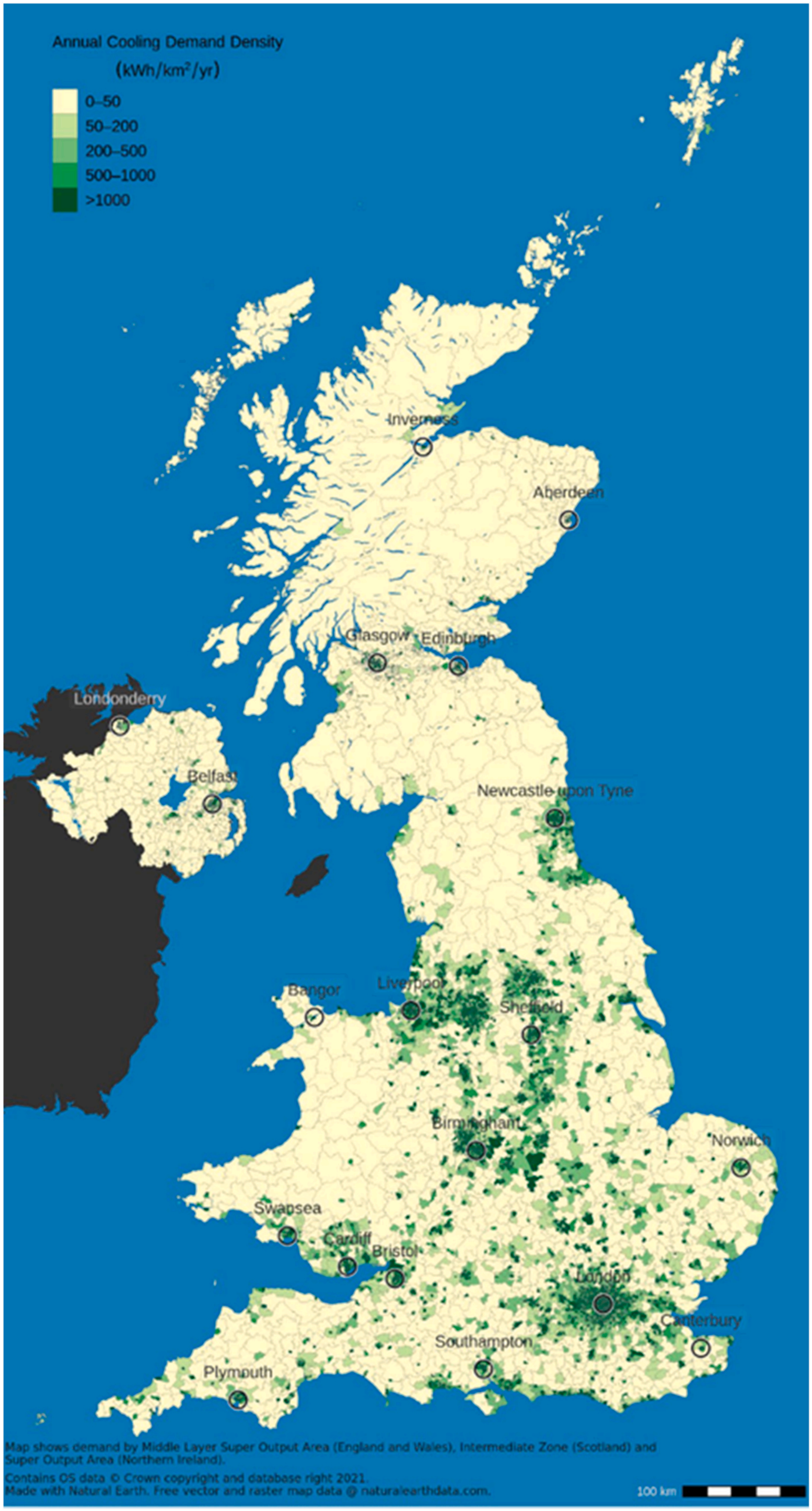

Fig. 8. Cooling demand density in the UK (taken from Ref. [1]).

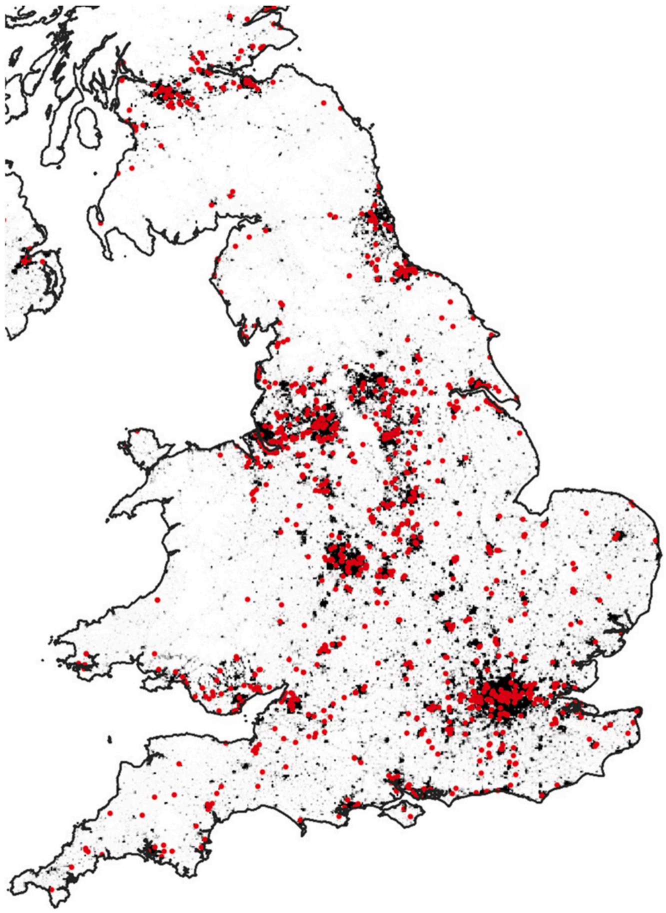

Fig. 9. Waste heat source locations (red) and population density (grayscale) in the UK (data compiled from Refs. [178,179]).

Scotland and England currently under construction. Various storage technologies provide an opportunity to store excess power and prevent curtailment [185]. The most efficient mechanism to store energy via UTES from wind which would otherwise be curtailed would be by using the electrical energy to power air sourced heat pumps which extract heat from the air for subsequent storage in the subsurface (e.g., Ref. [113]).

UTES technologies could support district heating systems integrating solar and curtailed wind energy sources. 4th generation district heating systems consider UTES as an integral tool for load shifting between summer and winter [186] which has been shown to be able to reduce the overall system costs [187–189]. The interaction between wind and solar power and UTES takes different forms due to differences in their generation curves. Solar power reliably produces an abundance of heat in the summer, making it the standard choice to complement seasonal thermal storage, see the Marstal system [190]. Wind on the other hand exhibits less seasonality and provides heat on a more irregular basis. While such interplay has seen less attention in research, the volume of curtailed wind energy in the UK makes storing this in UTES an attractive prospect. Particularly, as it can be viewed as an alternative to other types of storage, such as underground hydrogen, which can have low efficiencies (e.g., Ref. [191]).

There are however, issues surrounding the use of electricity and its conversion to heat. Some suggest a combined heat and power system that uses an electric boiler or phase change thermal energy storage with a power supply can improve wind utilisation in an economic way [185]. Others suggest photovoltaic thermal solar systems may be the most efficient heat and power systems, but at present such systems are experimental [192]. Exergy losses should be considered at all points of energy conversion. While exergy is lost in the process of converting electricity to heating, this is more sustainable than burning natural gas, with high exergy, to low-exergy heating demands. Additionally, there are also benefits such as the instant use in combination with fluctuating supply [193]. As exergy is destroyed in heat production [194] a better method of using curtailed wind energy or solar PV may be through powering heat pumps.

6. Electricity markets

There is clear potential for combining power to heat technologies, such as heat pumps and resistive heaters, with UTES. Therefore, it is important to understand the connected electricity markets which will be used to purchase electricity to generate the heat which can be stored in UTES. The current system entails significant price volatility with the potential for periods of very low (or even negative) price. The use of low-cost energy is fundamental to the overall economics of STES [195] and there is potential for the use of excess or curtailed energy to be incentivised with favourable tax rates and market mechanisms [92]. The lowest periods of price for grid electricity provide a key potential source of low-cost charge for STES and which could be taken advantage of in the UK.

The lowest prices are more likely to occur in the balancing intra-day markets or the day-ahead market [196]. If the overall balancing agreements are miscalculated, there may be more electricity produced than needed and, in this instance, negative prices can occur as the National Grid Electricity System Operator can pay some consumers to consume more. The lowest prices tend to occur during periods of low demand such as overnight, weekends and public holidays. The potential proliferation of various power-to-heat technologies is one demand side measure that could reduce the occurrence of negative pricing [197].

UTES may also benefit from long term supply contracts. Large scale electricity consumers can source electricity via long term supply contracts or power purchase agreements. There may be a natural alignment between low running cost suppliers and large electricity consumers that desire predictable prices [198]. A degree of long-term price certainty is also critical to providing investor confidence and a low cost of capital for STES projects.

Although long term supply contracts offer price certainty, they do not offer the lowest prices, which are available on the wholesale market (as highlighted above, on the intra-day or sometimes day-ahead markets). There are various incentives or mechanisms in the UK electricity retail sector that encourage the use of electricity at certain times. Time of Use tariffs are well established for larger electricity users (commercial and industrial customers with half hourly settlement) [199].

Nodal pricing involves making the price paid for generating electricity vary by location to a greater degree than it does currently or locational differentiation of prices at different nodes on the transmission network. The intention is to encourage greater locational flexibility (e.g., generation or storage), taking account of the real physical constraints in the network [200]. It is anticipated that more pricing granularity would exert upward pressure on prices in the most congested areas [201]. Although this is expected to result in more co-location of generation and storage, the impact on thermal energy storage is unclear.

7. Discussion and conclusions

This paper assessed the potential for UTES technology to be implemented in the UK. Spatial mapping from a series of sources were compiled for a high-level national overview. Spatial analysis of geological suitability for UTES, waste heat, curtailed renewable energy sources, heat demand, and the potential to repurpose existing infrastructure, such as oil and gas wells and flooded mines, indicate there is an opportunity for the implementation of different types of UTES technologies. In addition, electricity markets as a source for charge were considered, whilst storage capacities of ATES and MTES were compared with new estimates of BTES capacities calculated in this paper.

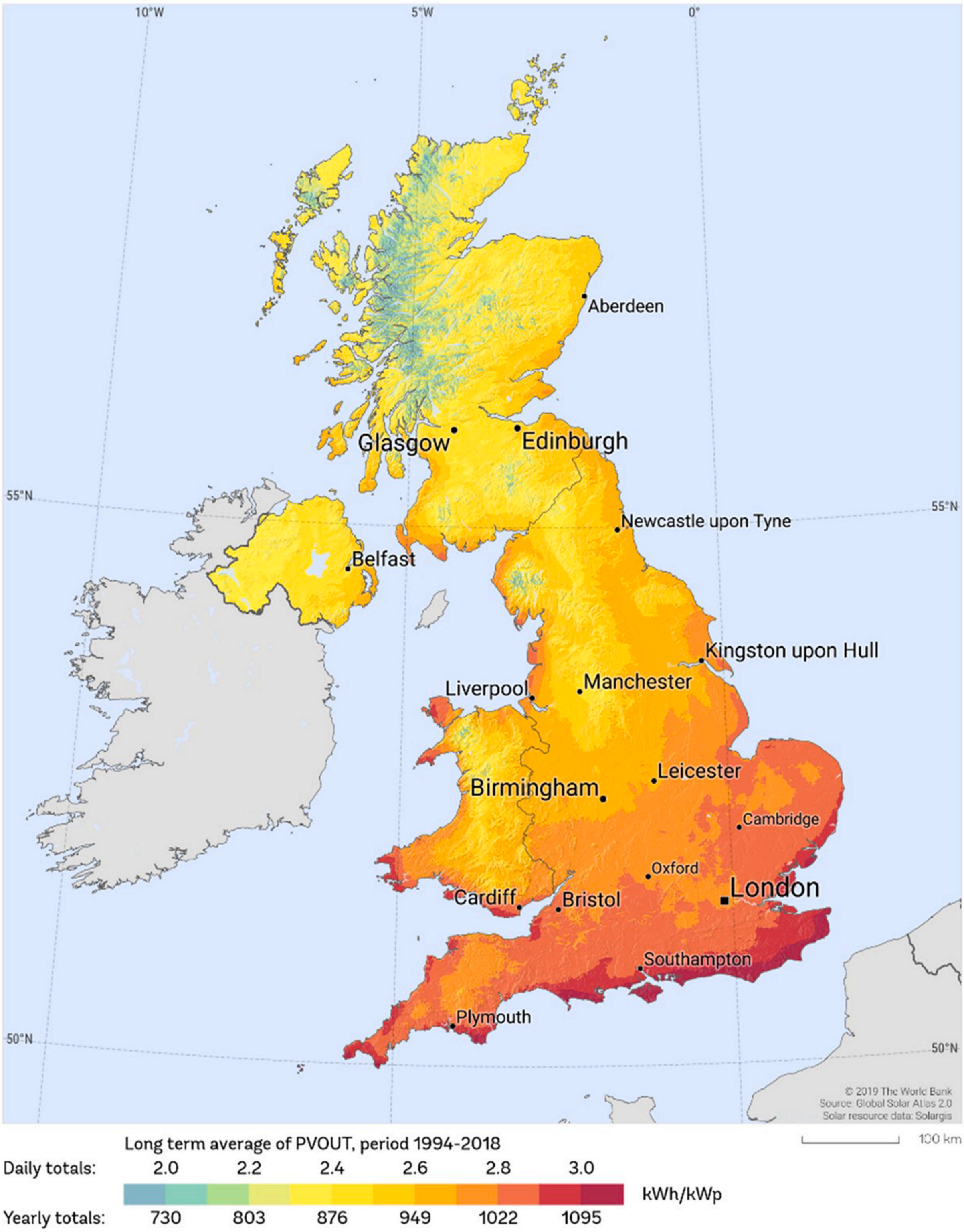

Fig. 10. Theoretical solar PV energy potential of the UK based on solar irradiation (taken from Ref. [183]).

TTES is widespread in all applications (including above ground) within the UK and used in over 11 million homes. It is also deployed in district heat networks, whilst PTES is used in one project [53]. PTES, and sometimes TTES, require more space, which may leave them potentially unfeasible for large scale UTES in densely populated areas within the UK. The UK has significant geospatial distributions of mines, aquifers and lithology suitable for UTES:

- Areas suitable for ATES are largely constrained to parts of England, with potential aquifers also located within Southern Wales, the Midland Valley in Scotland, and Northern Ireland. These tie in with major urban areas and cities within the UK, including those with the most heat demand and potential waste heat (i.e., London, Manchester, Cardiff, Glasgow, Edinburgh, and Birmingham).

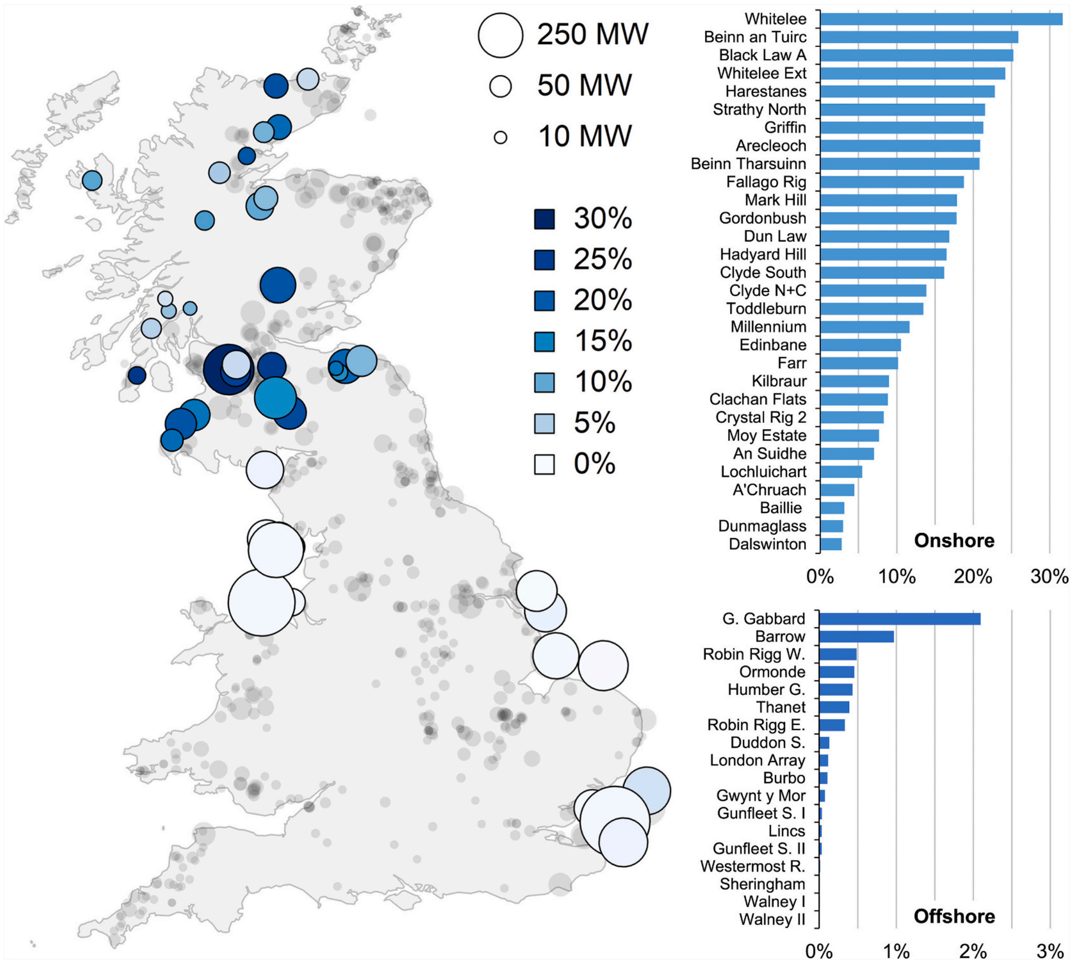

Fig. 11. Curtailment of wind power in the UK [184].

- Areas suitable for BTES in the UK are largely unrestricted and will depend on local conditions and groundwater flow. It has been theorised if geological conditions permit open-loop systems have a higher capacity so should be considered first. However, localities where BTES may be the most suited option include much of Wales and Scotland.
- Areas underlain by mines (MTES) include much of Northern England, Southern Wales and Southern Scotland. These do coincide with many major urban areas, such as Cardiff, Glasgow, Newcastle, Manchester.
- Future work should target localised investigation to compare different factors that impact UTES (outlined in section 2), as the geospatial analysis is to give a broad indication on potential.

High storage capacity of up to 250 EJ (69,444 TWh) for ATES and MTES combined were established using a new incremental increase of temperature (15 °C). This is significant and exceeds current demand for heating (436 TWh) and cooling (39 TWh) within the UK. For BTES, new estimates were provided for typical volumes used for thermal energy storage in the UK which might be used for small to larger scale systems (20^3–150^3 m^3). This equates to a range of values depending on the volume and temperature increase. These were between 17.6 GJ and 111 TJ, respectively (4.9 and 30,938 MWh).

Although the potential for UTES technology is high, there remain issues with subsurface geological knowledge, particularly for ATES systems. Obstacles remain, including problems with predicting secondary permeability in aquifers, preferred confined aquifers lead to reduced hydraulic properties and increased burial depths lead to the requirement of higher charge temperatures. It has however, been shown that the Permo-Triassic may be the most important aquifer as it has good properties for ATES and is geographically widespread.

Shallow BTES systems remain constrained to areas without groundwater flow (or to areas with Darcy velocity of less than c.1e-7m/s) [107–113]. Bedrock that is conducive for development has been identified in the study; whilst near surface superficial deposits could also allow local groundwater movement to inhibit BTES performance. In reality the array design and surface demand may dictate feasibility of implementation.

There are also projects aiming to de-risk UTES technology in the UK with pilot research geo-observatories set up on the north-western boundary of the Cheshire Basin (e.g., Ref. [202]) and at the Clyde Gateway, Glasgow (e.g., Ref. [78]). The former will allow research into operation of shallow ATES/BTES and testing of Permo-Triassic aquifers, the latter will allow testing of MTES. Both will have a series of boreholes for testing and observation, meaning they could prove pivotal in enhancing the local understanding of such systems and replication of technologies nationwide.

When considering surface components to UTES, heat demand and waste heat is concentrated over subsurface distributions of aquifers and mines, highlighting different sectors may be linked for STES due to the geographical proximity. Annually, the demand in the UK is 463 TWh for heating and 39 TWh for cooling [1], which is far lower than the estimated storage capacities. Hence, UTES technologies can technically store enough energy to meet UK heating and cooling demand. Yet, development remains limited due to commercialisation challenges, uncertainty around future cost reduction, uncertainty around performance of UTES technology, lack of heat storage knowledge in the UK and uncertainty in carbon savings [53]. Additionally, there is a large concentration of waste heat which could be stored in the low demand periods. It has been estimated 1404PJ (390 TWh) of waste heat is generated annually [34]. Both curtailed wind and excess solar energy can also be used as sources for UTES, with the former providing 3.53 TWh of curtailed energy in the UK [184] and the latter providing an average solar irradiation on a horizontal surface of 1000 kWh/m^2 per annum [180]. The waste heat and significant curtailed energy from wind and solar resources could therefore be suitable for UTES with the use of heat pumps.

In conclusion, the paper assessed a range of UTES applications for the UK, whilst considering the surficial demand and sources for heat storage. The increasing demand for heating and cooling in the UK provides a significant opportunity to store thermal energy from waste and renewable energy sources using UTES technology. UTES and STES can help with decarbonisation of heat in the UK. The largely untapped storage capacity demonstrates small increases in subsurface temperature can allow storage and utilisation with heat pumps or through district heat networks. The important role of heat demand is likely to dictate any efficient STES system; however, geographical sources of heat may also play a key role with waste heat also constrained to high population densities. The change in pricing structure of the electricity markets to include locational pricing could also be considered in future studies where STES is used with grid-connected power-to-heat technologies or use the electricity with heat pumps for ambient storage. STES can take advantage of corresponding geological and waste heat locations coinciding with the more populated areas, whilst evolving energy prices and markets can aid with low-cost supply of heat. Furthermore, STES can use the abundant solar energy generated in summer and curtailed wind energy. Future work should include a full economic analysis of the varying underground thermal energy storage technologies in the UK and internationally. At present, this is difficult to constrain as it will depend on many factors from storage volume size, subsurface conditions to the technology implemented.

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

No data was used for the research described in the article.

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