Applied Energy 376 (2024) 124096

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Aquifer Thermal Energy Storage for low carbon heating and cooling in the United Kingdom: Current status and future prospects

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ARTICLE INFO

Keywords:
Aquifer Thermal Energy Storage (ATES)
Underground Thermal Energy Storage (UTES)
Low carbon heating
Low carbon cooling
Sustainable energy
Geothermal energy

ABSTRACT

Aquifer Thermal Energy Storage (ATES) is an underground thermal energy storage technology that provides large capacity (of order MW_{th} to 10s MW_{th}), low carbon heating and cooling to large buildings and building complexes, or district heating/cooling networks. The technology operates through seasonal capture, storage and re-use of thermal energy in shallow aquifers. ATES could make a significant contribution to decarbonising UK heating and cooling, but uptake is currently very low: eleven low temperature (LT-ATES) systems currently operating in the UK meet <0.01% of the UK's heating and <0.5% of cooling demand. The Wandsworth Riverside Quarter development in London is analysed as a successful UK case study. The UK has large potential for widespread deployment of LT-ATES, due to its seasonal climate and the wide availability of suitable aquifers co-located with urban centres of high heating and cooling demand. ATES could supply ca. 61% of UK heating demand, and ca. 79% of cooling demand with a 13%–41% reduction in carbon emissions for heating, and 70%–94% reduction for cooling, compared to equivalent ground- or air-sourced heat pump systems. However, problems with design and operation in some UK systems have caused sub-optimal performance. The UK can benefit from experience of both successful and unsuccessful deployments but these need to be more widely reported. Raising awareness, developing policies to encourage uptake, streamlining regulations and developing expertise are essential to unlock the potential of ATES technology in the UK, which requires engagement with policymakers, regulators, industry stakeholders and the general public.

1. Introduction

In common with many temperate countries, space and water heating accounts for >70% of the UK's final energy consumption, excluding transport [1]. To meet this heating demand, the UK is reliant on burning fossil fuels, particularly natural gas. Heating of buildings accounts for ca. 23% of the UK's greenhouse gas emissions [2]. Decarbonising heating and cooling is essential to achieve net-zero emissions, but the sector is one of the most difficult to abate.

One of the challenges of meeting the UK's heating demand from renewable sources is that demand is both highly seasonal and out of phase with periods of high renewable energy supply [3,4]. To address this issue, large scale seasonal energy storage must be integrated in pathways to decarbonise heating and cooling [5]. The subsurface offers large capacity for storage of thermal energy (of order 2–4 MJ/(m^3 K); [6]). Storage of sensible heat in the subsurface is termed Underground Thermal Energy Storage (UTES). Waste heat from buildings, industrial processes or excess renewable energy generation in the summer can be stored in the subsurface and used for heating in the winter [4]. Conversely, storage of cool in the winter can be used to provide cooling in the summer.

Aquifer Thermal Energy Storage (ATES) is a type of UTES that stores warmed or cooled groundwater in naturally porous, permeable underground rocks and uses this to provide low carbon heating and cooling. The aim of this study is to assess the current status and future potential of ATES in the UK. As we show, the number of active and planned UK ATES installations is small and awareness of the technology is low. Given the rapid growth of ATES deployments in neighbouring countries and its potential to provide large scale, low carbon heating and cooling, there is a need to assess whether the technology should be implemented at scale in the UK.

The objectives of the study are to (i) identify operating ATES systems in the UK and assess their current contribution to heating and cooling; (ii) report the first performance analysis of an operating UK installation as a case study; (iii) assess the potential for widespread ATES deployment across the UK; (iv) estimate the proportion of UK heating and cooling demand that could be supplied by ATES; (v)

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https://doi.org/10.1016/j.apenergy.2024.124096
Received 22 February 2024; Received in revised form 28 June 2024; Accepted 29 July 2024

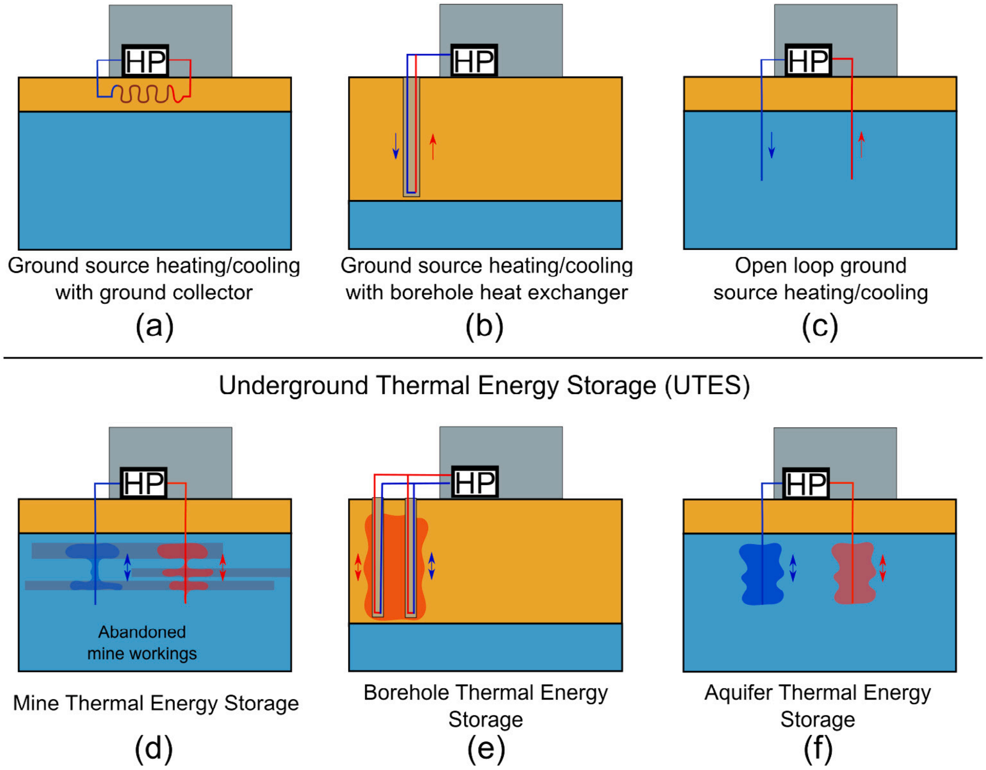

Fig. 1. (a–c) Shallow geothermal technologies that source energy from the subsurface for heating and/or cooling without energy storage. Methods (a–c) are illustrated here for heating applications but they can also be used for cooling and combined heating and cooling. (d–f) Shallow geothermal technologies with storage (UTES). (d) Mine Thermal Energy Storage (MTES), (e) Borehole Thermal Energy Storage (BTES) and (f) Aquifer Thermal Energy Storage (ATES). The yellow layer represents an aquitard, whilst the blue layer represents an aquifer. HP indicates a heat pump, which is typically required to provide heating and may also be required to provide cooling.
Source: Modified from [7].

compare the predicted electricity demand and CO_2 emissions of ATES in the UK against comparable shallow geothermal technologies that utilise similar borehole and surface infrastructure, and (vi) identify barriers to widespread uptake of ATES in the UK. The study is novel because it is the first to address the deployment of ATES in the UK, providing national estimates of ATES capacity and decarbonisation potential. Although UK focused, the approach, methods and analysis are applicable to many other emerging markets.

The remainder of this introduction provides a short background on ATES in the context of geothermal technologies. Section 2 details the methods used here for analysing ATES performance, UK potential, and CO_2 emissions savings. Section 3 gives an overview of ATES in the UK, and Section 4 analyses the performance of a large UK installation. Section 5 calculates the share of UK heating and cooling demand that could be met by ATES; Section 6 calculates the carbon intensity of heat and cool delivered, and savings relative to other low-carbon technologies. Section 7 considers the challenges that ATES faces in the UK, Section 8 discusses the wider context of the paper's findings, and Section 9 concludes.

1.1. Shallow geothermal technologies for heating and cooling

ATES systems are one of a larger group of shallow geothermal technologies that can provide low carbon heating and/or cooling to the built environment (Fig. 1). These technologies use the shallow subsurface to store and/or source heat and/or cool. Thermal energy is transported from the subsurface using one or more boreholes and a carrier fluid. A heat exchanger transfers the energy from the carrier fluid to a working fluid on the building side. A heat pump can increase or decrease the working fluid temperature if required.

Shallow geothermal systems can be broadly subdivided into those that source heat or cool from the subsurface but do not store energy (e.g. Fig. 1a–c), and UTES systems in which heat or cool is stored for later use (e.g. Fig. 1d–f). In each case, systems can be further classified as closed- or open-loop. In closed-loop systems (Fig. 1a,b,e), a carrier fluid is circulated through a network of pipes or boreholes which are buried in the ground. There is heat but not mass exchange between the pipes/boreholes and surrounding rock or soil. In open-loop systems (Fig. 1c,d,f), thermal energy is stored and/or produced by directly injecting or extracting groundwater from the subsurface via one or more boreholes.

Heating and/or cooling systems that use the subsurface (ground) to source the energy supplied to a heat pump are often broadly termed 'Ground Source Heat Pump' (GSHP) or 'Ground Source Heating and Cooling' (GSHC) systems. This terminology can introduce confusion owing to the different approaches used to store and/or extract heat and/or cool in the subsurface across different technologies, which impacts system design, operation, monitoring and regulation. In particular, the importance of subsurface geology and groundwater flow, in controlling the supply and storage of heat and cool in open-loop systems and large closed-loop systems, marks these systems out as distinct from GSHP systems with shallow ground collector loops (Fig. 1a): they are geothermal technologies. Open loop systems are sometimes termed Groundwater Heat Pump (GWHP) or Groundwater Heating and Cooling (GWHC) systems; we use the former to describe systems that provide only heating or cooling, and the latter to describe systems that provide heating and cooling.

1.2. Aquifer Thermal Energy Storage (ATES)

ATES is a proven technology capable of delivering low carbon heating and cooling at scale with significant international uptake [8]. ATES is a type of UTES in which porous, permeable sediments or rocks underground are used to store waste heat and cool for use when

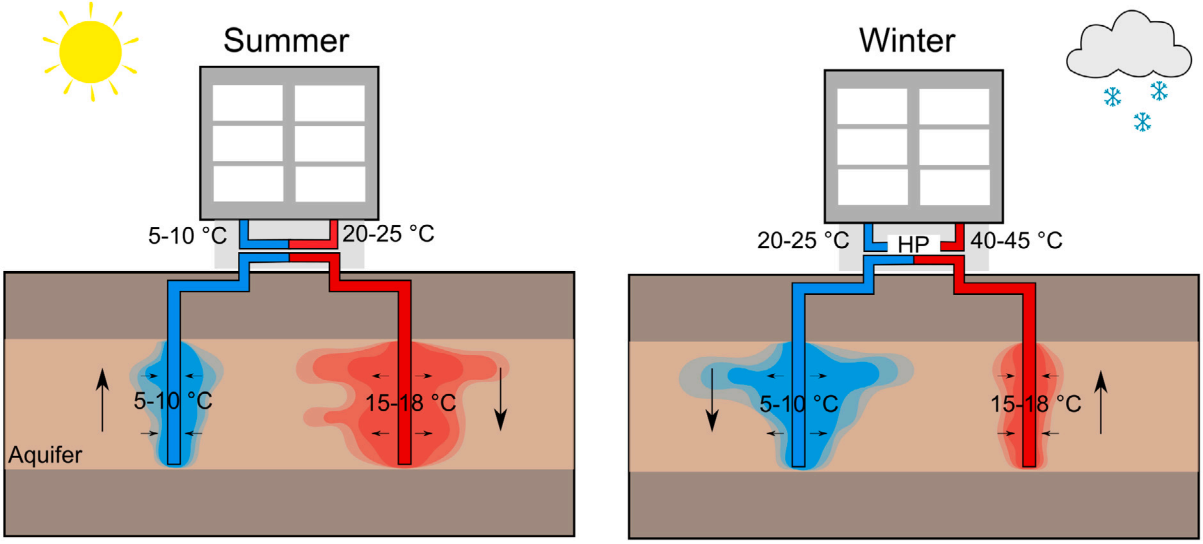

Fig. 2. Operational principle of low-temperature ATES in summer (left) and winter (right). HP = heat pump.
Source: Modified from [9].

there is demand for heating and cooling. Here, we primarily consider low-temperature (LT-ATES) systems in which storage temperatures are typically of order 15–20 °C at the warm well(s) and 5–10 °C at the cold well(s), because these systems dominate worldwide [8]; moreover, a number of LT-ATES systems are currently operating in the UK. The potential for deploying high-temperature (HT-ATES) systems in the UK is briefly considered later. The basic requirements for LT-ATES deployments for seasonal storage and re-use of energy are (i) a seasonal climate with distinct periods of heating and cooling demand, and (ii) a suitable storage aquifer (porous, permeable rock or sediments/drift) at shallow depth (typically up to ca. 200 m below ground surface) beneath the building(s) supplied by the system.

The basic operational principle of seasonal ATES is illustrated in Fig. 2 [8,10,11]. In winter, warm groundwater is pumped from one (or more) warm well(s). Heat is exchanged from the groundwater to a working fluid via a heat exchanger. A heat pump is used to raise the temperature of the working fluid which is circulated through the building(s) supplied by the system to provide heating. The cooled working fluid is returned to the heat exchanger to be warmed by the groundwater, and the cooled groundwater leaving the heat exchanger is injected into the aquifer via one (or more) cold well(s). In summer, the process is reversed: cool groundwater is pumped from the cold well(s) and the working fluid is cooled by the groundwater via the heat exchanger to deliver cooling to the building(s) supplied by the system. In most installations, cooling can be delivered directly without a heat pump [8,10]. This is known as direct cooling. In some, a heat pump is used to further cool the working fluid. The warmed working fluid is returned to the heat exchanger to be cooled by the groundwater, and the warmed groundwater leaving the heat exchanger is injected into the aquifer via the warm well(s) for later production during the next winter.

In Fig. 2 only two wells are shown: a warm well and a cool well, comprising a well doublet. In practice, the number of well doublets can be increased to deliver higher heating and cooling power and storage capacity [8]. To ensure sustainable delivery of heating and cooling, the ATES system should be engineered to be balanced; that is, to store and use equal amounts of heat and cool on average over each annual cycle [12]. A balanced system is less likely to induce long term temperature changes in the aquifer, or experience thermal interference of the warm and cool groundwater plumes in the aquifer leading to a reduction of energy storage efficiency [12,13]. If the cooling and heating demand is not balanced, additional low carbon sources of heating and cooling sources can be deployed to achieve balance [14]. Fig. 2 shows capture and re-use of waste heat and cool from the same building(s). However, ATES can also be used to capture waste heat or cool from one source and store it for use elsewhere; for example, waste heat from industry can be captured in summer and stored to provide heating to nearby buildings in winter.

1.3. ATES compared to other shallow geothermal technologies

ATES systems have several distinctive characteristics compared to other shallow geothermal technologies for heating and cooling. First, ATES systems are exclusively open-loop. Second, ATES systems employ bi-directional wells which inject or produce groundwater depending on demand for heating or cooling. The wells are defined by the temperature of the groundwater that is stored and produced, so are termed 'warm' (or 'hot') and 'cool' (or 'cold'). They cannot be defined as 'injection' and 'production' wells, in contrast to uni-directional, open-loop shallow geothermal installations such as GWHC systems (e.g. Fig. 1c) in which one (or more) well(s) produce groundwater to deliver heating or cooling and one (or more) well(s) dump waste heat or cool which is not reused. These uni-directional systems do not fit the definition of ATES because there is no storage and reuse of thermal energy. Finally, an ATES system is distinct from other types of open-loop UTES in using a natural subsurface aquifer for energy storage. Other open-loop UTES technologies store thermal energy in man-made reservoirs such as abandoned mines, natural caverns or specially constructed tanks or pits [8].

ATES is an attractive option to decarbonise heating and cooling of the built environment for several reasons. First, it is characterised by large storage (of order 100s to 1000s MWh_{th}) and power (or order MW_{th} to 10s MW_{th}) capacities and can be used to supply large buildings or complexes of buildings, or district heating/cooling networks [8,15]. ATES systems have the scale to supply 'heat as a service' (HAAS) or 'cool and heat as a service' (CHAAS) [16]. Storage capacity is large compared to man-made reservoirs (including thermochemical reservoirs) because of the very large volumes naturally available in the subsurface; losses during storage in a well designed system are primarily due to conductive exchange with surrounding rock, which is limited by low rock thermal conductivity (of order 2–4 W/mK; [17]). Power capacity is large because pumping groundwater into and out of the storage reservoir allows rapid transport of energy via advection, especially compared to closed-loop systems that rely on conductive heat transport for heat exchange in the subsurface. Power capacity in ATES systems can be scaled by increasing the number of well doublets. Despite the large capacity, the surface footprint of ATES systems is small, comprising a limited number of wells (typically ca. 2–30 depending on system capacity) of small diameter (ca. 20–70 cm) that can be concealed under access covers. Access is required only occasionally for maintenance.

Second, ATES has the advantage of providing both heating and cooling. Cooling demand has received comparatively less attention in the UK, but is predicted to increase as a warming climate brings hotter summers [18–20]. Growth in cooling demand is currently 5% in London, the highest rate in the world [20]. Since 1990, global energy demand for space cooling has more than tripled and the associated GHG emissions have doubled [19]. As we show here, peak cooling demand in most UK ATES installations already matches or exceeds peak heating demand. The provision of low carbon cooling using ATES is therefore important to meet growing demand.

Third, a well designed ATES system offers sustainable heating and cooling because energy is stored and re-used, rather than extracted from the subsurface. As we show here, ATES offers significant reductions in carbon emissions and electrical energy consumption compared to similar shallow open-loop geothermal technologies such as GWHC (Fig. 1c) because groundwater sourced for heating has been pre-warmed by previous storage of waste heat; likewise, groundwater sourced for cooling has been pre-cooled by previous storage of waste cool. This can allow cooling be supplied directly without use of a heat pump [8,10].

1.4. International context

A number of worldwide reviews on the status of ATES technology have been published [8,21,22] so only a short summary of the key findings is reported here. ATES was initially deployed in the 1960s in Shanghai to provide cooling to factories. The technology grew rapidly, with more than 400 wells being drilled in over 20 cities. Systems were then installed in other countries, including Switzerland (1974), the USA (1976), France (1983), the Netherlands (1985) and Sweden (1991). The Netherlands experienced rapid growth of the technology in the 2000s. As of today, there are approximately 3500 ATES systems worldwide, with ca. 3000 of these located in the Netherlands [23].

One of the key drivers for the rapid uptake of ATES in the Netherlands was the introduction of building efficiency regulations [24]. Support from the Dutch government via incentive programmes [8] as well as a shift in public perception on natural gas [25] were also important factors driving uptake. The Netherlands hosts the current largest ATES system at the University of Technology in Eindhoven: a 36 well system delivering 20 MW_{th} heating and cooling. The estimated CO_2 savings from this installation are of order 13,300 tonnes/yr [26]. Most of the remaining ATES systems are located in Sweden, Denmark and Belgium, which are currently experiencing rapid growth [8,21,27]. The Netherlands remains, to date, the clear leader in ATES technology adoption.

2. Methods

2.1. Identification of current UK ATES installations

As yet, there is no centralised UK database of ATES installations and they are often categorised as GSHP or GSHC systems, so are not always straightforward to identify. The systems reported here were identified using data provided by the Environmental Agency, the Environmental Agency for Northern Ireland, the Scottish Environmental Protection Agency and Natural Resources Wales, by searching for wells licensed for both abstraction and discharge of groundwater. ATES system installers, owners and operators were also directly approached where these could be identified. Not all operators engaged with the study and only one shared sufficient operational data for system performance to be analysed.

2.2. ATES system performance analysis

As an ATES system is operated, plumes of warm and cold groundwater are created in the aquifer around the wells. In a homogeneous aquifer (i.e. one with spatially uniform porosity and permeability), the plumes form cylinders around the well(s) with a radius that increases and decreases as warm and cool water is alternately pumped into, and out of, the aquifer. The maximum radius of each cylinder, within which the temperature will change during warm or cool storage, is termed the ‘thermal radius’ R_{th} and can be estimated by [28]

$$R_{th} = \sqrt{\frac{c_w V_i}{c_{aq} \pi L_s}} \tag{1}$$

where V_i is the volume of water injected into the well during a given heating or cooling period, c_w is the volumetric heat capacity of water, c_{aq} the volumetric heat capacity of the reservoir and L_s the well screen length (the portion of the well open to flow) (see Table 1). The thermal radius as defined in Eq. (1) does not account for conduction, dispersion, vertical flow or geologic heterogeneity and typically represents a minimum estimate of the actual thermal radius [29].

Estimating the thermal radius is useful when planning an ATES system to ensure cold and warm wells are spaced far enough apart to avoid negative interference, which occurs when warm and cold plumes overlap. Negative thermal interference reduces energy storage efficiency, because cooled aquifer rock around the cold wells is warmed during storage of warm water and *vice-versa*. To avoid this, some regulatory authorities (such as in the Netherlands) require cold and warm wells to be separated by a minimum distance of $3R_{th}$ [30]. The thermal radius can also be used to estimate the spacing required between new ATES systems and other systems that exploit the subsurface, such as groundwater abstractions wells or other ground source heating/cooling schemes.

Sustainable operation of ATES systems requires a balance between produced heat and cool to ensure the average aquifer temperature does not increase or decrease over time. The balance of produced heat and cool is quantified by the energy balance ratio EBR, defined as [12]

$$\mathrm{EBR} = \frac{E_{p,c} - E_{p,h}}{E_{p,c} + E_{p,h}} \tag{2}$$

where $E_{p,c}$ is the energy extracted for cooling and $E_{p,h}$ is the energy extracted for heating. E_p for a given period when the system is operated in heating or cooling mode is given by

$$E_p = \int_{ex} c_w q_p (T_p - T_i) dt \tag{3}$$

where the integral over ‘ex’ denotes the period of groundwater production, q_p is the production flowrate (taken to be positive during heating, and negative during cooling; the corresponding injection flowrate is negative during heating and positive during cooling), T_p is the production temperature and T_i is the injection temperature; note that we neglect here small temperature changes caused by energy losses as groundwater moves through surface pipework or other infrastructure. In heating mode, $T_p = T_{p,h}$ and $T_i = T_{i,c}$, where $T_{p,h}$ is the production temperature from the warm well(s) and $T_{i,c}$ is the injection temperature at the cool well(s); in cooling mode, $T_p = T_{p,c}$ and $T_i = T_{i,h}$ where $T_{p,h}$ is the production temperature of the cool well(s) and $T_{i,c}$ is the injection temperature at the warm well(s). An EBR close to zero indicates that the system is balanced [12].

Similar to the EBR, a volume balance ratio (VBR) can also be defined to quantify the relative volumes of groundwater extracted and injected in heating and cooling modes. The VBR is defined as [12]

$$\mathrm{VBR} = \frac{V_{p,c} - V_{p,h}}{V_{p,c} + V_{p,h}} \tag{4}$$

where $V_{p,c}$ is the volume extracted for cooling and $V_{p,h}$ is the volume extracted for heating. Note that the all groundwater extracted from the

Table 1
Nomenclature.

Variable or Acronym	Definition
A	Surface area of aquifer
ASHP	Air Source Heat Pump
ATES	Aquifer Thermal Energy Storage
BTES	Borehole Thermal Energy Storage
c_{aq}	Aquifer volumetric heat capacity
c_w	Groundwater volumetric heat capacity
COP (–)	Coefficient of Performance of the heat pump
ex	extraction
e_{hp}	Scaling factor that accounts for the heat pump contribution
$e_{hp,c}$	Heat pump contribution during cooling
$e_{hp,h}$	Heat pump contribution during heating
E_d	Energy demand for heating or cooling
E_e	Electrical energy
$E_{e,hp}$	Electrical energy supplied to the heat pump
$E_{e,t}$	Total electrical energy supplied to the system
E_p	Energy produced from the aquifer
$E_{p,c}$	Energy produced from the aquifer during cooling
$E_{p,h}$	Energy produced from the aquifer during heating
E_s	Energy supplied to the building(s)
$E_{s,c}$	Energy supplied to the building(s) during cooling
$E_{s,h}$	Energy supplied to the building(s) during heating
EBR	Energy Balance Ratio
f	Fraction of aquifer available for ATES deployment in a given area
GHG	Greenhouse Gas
GSHC	Ground Source Heating and Cooling
GSHP	Ground Source Heat Pump
GWHC	Ground Water Heating and Cooling
GWHP	Ground Water Heat Pump
HaaS	Heat as a Service
HP	Heat Pump
HT	High Temperature
HVAC	Heating, Ventilation and Air Conditioning
in	injection
L_s	Screen length
LT	Low Temperature
MTES	Mine Thermal Energy Storage
P_e	Electrical energy for pumping per unit of groundwater volume
q_i	Volumetric rate of groundwater injection
q_p	Volumetric rate of groundwater production
R_T	Thermal recovery factor
R_{th}	Thermal radius
SCOP	System coefficient of performance
T_{aq}	Ambient groundwater temperature in the aquifer
T_i	Temperature of injected groundwater
$T_{i,c}$	Temperature of groundwater injected into the cool well(s)
$T_{i,h}$	Temperature of groundwater injected into the warm well(s)
T_p	Temperature of produced groundwater
$T_{p,c}$	Temperature of groundwater produced from the cool well(s)
$T_{p,h}$	Temperature of groundwater produced from the warm well(s)
T_s	Temperature supplied to the building(s)
$T_{s,c}$	Temperature supplied to the building(s) during cooling
$T_{s,h}$	Temperature supplied to the building(s) during heating
ΔT_g	Difference in groundwater temperature between warm and cool wells
ΔT_{hp}	Temperature change induced by the heat pump
UTES	Underground Thermal Energy Storage
V_i	Injected volume of water
$V_{i,c}$	Injected volume of water into the cool well(s)
$V_{i,h}$	Injected volume of water into the warm well(s)
V_p	Produced volume of water
$V_{p,c}$	Produced volume of water from the cool well(s)
$V_{p,h}$	Produced volume of water from the warm well(s)
VBR	Volume balance ratio
WRQ	Wandsworth Riverside Quarter

cool well(s) must be re-injected at the warm well(s) and *vice-versa*, so $V_i = V_p$ during a given period of heating or cooling.

Finally, the thermal recovery factor R_T quantifies how efficiently thermal energy is recovered from the subsurface. R_T is defined as the ratio of the warm or cool energy recovered to the energy stored in the previous period [31]

$$R_T = \frac{\int_{ex} q_p(T_p - T_{aq})\,dt}{\int_{in} q_i(T_i - T_{aq})\,dt} \tag{5}$$

where the integral over 'in' denotes the period of groundwater injection, q_i is the injection flowrate and T_{aq} is the average initial undisturbed aquifer temperature. R_T can be calculated over a single cycle (one year of operation) or over longer periods of system operation.

2.3. Heating and cooling energy supplied by ATES

The energy extracted from the aquifer and delivered to the heat exchanger in an ATES system is usually calculated using Eq. (3). In a balanced system, Eq. (3) can be re-written in terms of the (approximately) constant ambient aquifer temperature T_{aq} to yield the following expressions for heating and cooling, respectively [32]

$$E_{p,h} = \int_{ex} c_w q_p(T_{aq} - T_{i,c})\,dt + R_T \int_{in} c_w q_i(T_{aq} - T_{i,w})\,dt \tag{6}$$

$$E_{p,c} = \int_{ex} c_w q_p(T_{aq} - T_{i,h})\,dt + R_T \int_{in} c_w q_i(T_{i,c} - T_{aq})\,dt \tag{7}$$

where the second term on the right-hand-side represents recovery of heat or cool stored in the previous cooling or heating period. The advantage of expressing energy extraction in this way is that the additional energy supplied by an ATES system, as compared to a unidirectional GWHC system, is readily apparent: the first term on the right-hand-side of Eqs. (6) and (7) represents the energy supplied by producing water at ambient temperature for heating (Eq. (6)) and cooling (Eq. (7)); this is the energy supplied by a GWHC system. The second term on the right-hand-side of Eqs. (6) and (7) represents the additional energy supplied by storing heat and cool in an ATES system. The thermal recovery factor (R_T) of an ATES system can therefore be understood as a measure of the additional low carbon energy delivered from the aquifer by energy storage compared to a GWHC system. We make use of this in the next section.

The energy supplied to the building-side of the system over a given heating or cooling period includes the contribution of the heat pump; Eqs. (6) and (7) can be extended to yield

$$E_{s,h} = E_{p,h}e_{hp,h} = e_{hp,h}\int_{ex} c_w q_p(T_{aq}-T_{i,c})\,dt + e_{hp,h}R_T\int_{in} c_w q_i(T_{i,h}-T_{aq})\,dt \tag{8}$$

$$E_{s,c} = E_{p,c}e_{hp,c} = e_{hp,c}\int_{ex} c_w q_p(T_{i,h}-T_{aq})\,dt + e_{hp,c}R_T\int_{in} c_w q_i(T_{aq}-T_{i,c})\,dt \tag{9}$$

where a constant (averaged) heat pump contribution is assumed, represented by e_{hp} and given by

$$e_{hp} = \mathrm{COP}/(\mathrm{COP} - 1) \tag{10}$$

The Coefficient of Performance (COP) over the period is given by

$$\mathrm{COP} = E_s/E_{e,hp} \tag{11}$$

where E_s denotes the total heating or cooling energy supplied by the heat pump and $E_{e,hp}$ denotes the electrical energy used by the heat pump.

To estimate the heating and cooling energy that can be supplied by ATES over a seasonal (annual) cycle, the time integrals in Eqs. (8) and (9) were replaced here by average values of volumetric heat capacity (c_w) and temperature (T), and the total volumes of pumped groundwater (V). To ensure sustainable operation, volume and energy balance are imposed, so $V_{i,h} = V_{i,c} = V_{p,h} = V_{p,c}$ and $(T_{i,w} - T_{aq}) = (T_{aq} - T_{i,c}) = \Delta T_g$ where T_i represents the average injection temperature over a storage period. Consistent with many ATES installations [8,10], systems are assumed here to provide direct cooling without use of a

Table 2

Summary of uncertainty ranges used in the Monte-Carlo analysis of ATES heating and cooling supply. A triangular distribution is assumed for each parameter. See Appendix A for further explanation of the ranges chosen.

Variable	Minimum	Most likely	Maximum
Change in groundwater temp. (ΔT_g) (°C)	2	5	8
Thermal recovery factor (R_T) (–)	0.2	0.5	1
Effective screen length (L_s) (m)	2	20	100
Fraction of aquifer area available (f) (–)	0	1/5	2/5
Aquifer volumetric heat capacity (c_{aq}) (kJ K^{-1} m^{-3})	2250	2600	3000
COP (–)	4	4.8	5.5

heat pump. Given these assumptions, the annual heating and cooling energy that can be supplied by an ATES system can be obtained from Eqs. (8) and (9), and is given, respectively, by

$$E_{s,h} = c_w V_{p,h} \Delta T_g (1 + R_T) e_{hp,h} \tag{12}$$

$$E_{s,c} = c_w V_{p,c} \Delta T_g (1 + R_T) \tag{13}$$

Our approach was to estimate the annual heating and cooling energy that ATES could deliver per unit land area A (i.e. the power density; [7]) for comparison with annual heating and cooling demand data. Power density is a useful measure of the heating and cooling capacity of ATES because it accounts both for the rate at which energy can be produced and the space available for deployment; this latter factor is particularly important in urban areas with high heating and cooling demand [7].

Rather than the volume of pumped groundwater, we estimated the volume of aquifer available for ATES per km^2 as fAL_s, where L_s is the average effective screen length in area A and f denotes the fraction of the surface (aquifer) area that can be occupied by the warm or cool plumes. The annual heating and cooling energy per km^2 that can be supplied by ATES is then given, respectively, by

$$E_{s,h} = c_{aq} f (1000^2) L_s \Delta T_g (1 + R_T) e_{hp,h} \tag{14}$$

$$E_{s,c} = c_{aq} f (1000^2) L_s \Delta T_g (1 + R_T) \tag{15}$$

The performance of ATES systems can be influenced by various factors, including aquifer characteristics, seasonal variations in temperature, and system design. Predicting long-term performance can be challenging, leading to uncertainty regarding operational efficiency. Here, a Monte-Carlo approach was used to calculate the annual heating and cooling energy per km^2 using Eqs. (14) and (15) and a range of different values for the key uncertain variables (Table 2; see Appendix A for further details on the choice of probability distributions). In its simplest form, a Monte-Carlo simulation comprises numerous evaluations (trials) of an objective function, in which the value of each uncertain input variable in each trial is drawn at random from a probability distribution [33].

The spatial distributions of UK annual heating and cooling demand were determined from the HotMaps dataset [34]. Demand variability from year to year was derived using the Demand.ninja model [20], based on analysis of 43 years of historical weather data spanning 1980 to 2022. The resulting maps show average annual heating and cooling demand over the period 2010–2022.

A Monte-Carlo approach was used again to calculate the proportion of UK total heating and cooling demand that could be supplied using ATES. In each km^2 that contains a suitable aquifer, the heating or cooling energy that could be supplied by ATES (E_s) was sampled from a curve fitted to the annual heating or cooling energy supply per km^2 calculated as described above, and the heating or cooling demand (E_d) was sampled from the corresponding demand map. If $E_s > E_d$, we set $E_s = E_d$ to ensure the energy supplied in a given km^2 cannot exceed demand. If there is no aquifer, then $E_s = 0$. Summing over E_d in each km^2 gives the total heating or cooling demand; likewise, summing over E_s gives the total potential heating or cooling supply using ATES.

2.4. Electricity demand and carbon emissions from ATES systems and comparable heating and cooling technologies

The carbon emissions per unit thermal energy delivered were estimated here in a two-step process. First, we estimated the electrical energy required to supply unit heating or cooling thermal energy to the building; second, we calculated the CO$_2$ emissions using published data for the carbon intensity of UK electricity generation (Fig. 3B). Electrical energy is required to supply the heat pump, and also to produce groundwater, pass this groundwater through the heat exchanger and inject it back into the aquifer, along with operation of control systems and ancillary pumps on the building side.

The electrical energy required by the heat pump to supply unit heating or cooling energy to the building can be calculated from Eq. (11) and is given by

$$E_{e,hp} = 1/\mathrm{COP} \tag{16}$$

To calculate the energy required for groundwater pumping, we determined the volume of groundwater required to supply unit heating or cooling energy, and combined this with published values of the electrical energy required per unit volume groundwater production (P_e). We assumed a heat pump may be required for both heating and cooling, and used Eq. (12) which, when combined with Eqs. (10) and (11), yields

$$V_p = \frac{(\mathrm{COP} - 1)}{c_w \Delta T_g (1 + R_T)\mathrm{COP}} \tag{17}$$

The COP of the heat pump depends on the temperature change ΔT_{hp} that must be imposed between groundwater supplied to the pump, and heating or cooling supplied by the pump to the building, expressed as

$$\Delta T_{hp} = |T_s - T_p| \tag{18}$$

where T_s is the temperature supplied to the building by the heat pump and T_p is the temperature supplied to the heat pump from the aquifer. During heating, $T_s = T_{s,h}$ and $T_p = T_{p,h}$; during cooling, $T_s = T_{s,c}$ and $T_p = T_{p,c}$. Here we accounted for the heat pump COP by testing different building-side temperatures for heating and cooling (Table 3). For simplicity, we assumed the COP of the heat pump is the same for a given temperature change irrespective of whether it is used to deliver heating or cooling, and described the COP as a function of temperature change using a regression fitted to measured data (Fig. 3A) which is described using the coefficients a, c and d and the exponent b in Table 3. For heating, we chose from a range of building supply temperatures (Table 3). For cooling, we again assumed an ATES system supplies direct cooling without use of a heat pump, in which case Eq. (17) becomes

$$V_p = \frac{1}{c_w \Delta T_g (1 + R_T)} \tag{19}$$

and the temperature of the cooling fluid supplied to the building is given by

$$T_{s,c} = T_{aq} - \Delta T_g R_T \tag{20}$$

The total electrical energy required to deliver unit heating or cooling energy to the building is given by

$$E_{e,t} = E_{e,hp} + P_e V_p \tag{21}$$

As discussed in the previous section, the energy delivered from the aquifer by a balanced ATES system with zero thermal recovery ($T_r = 0$) is equivalent to the energy delivered by a balanced GWHC

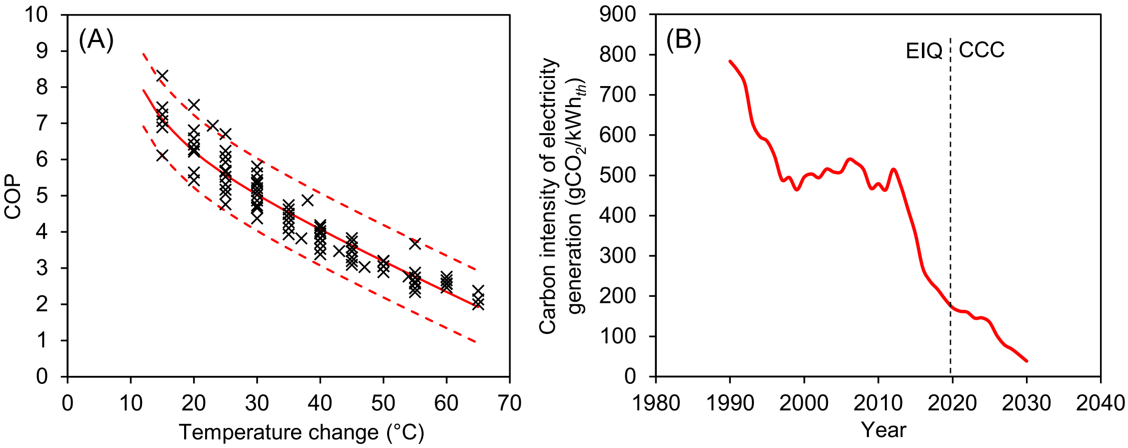

Fig. 3. (A) typical heat pump COP and (B) carbon intensity for the UK energy mix. The regression in (A) is given by an equation of the form COP $= a\Delta T_{hp}^{-b} + c\Delta T_{hp} + d$ where ΔT_{hp} is the temperature change across the heat pump from the aquifer supply to the building supply; data from [35,36]. The regression is chosen to ensure the COP tends to large values as ΔT_{hp} tends to zero. Historical carbon intensity data in (B) from Electric Insights (EIQ) [37] and future predictions from the UK Climate Change Committee (CCC) [38].

Table 3
Summary of uncertainty ranges used in the Monte-Carlo analysis of electricity consumption and CO_2 emissions. A triangular distribution is assumed for each parameter. See Appendix B for further explanation of the ranges chosen.

Variable	Minimum	Most likely	Maximum
Ambient aquifer temp. (T_{aq}) (°C)	8	11	14
Change in groundwater temp. (ΔT_g) (°C)		Table 2	
Thermal recovery factor (R_T) (–)		Table 2	
Electrical energy to pump groundwater (P_e) (kJ/m^3)	300	600	1200
Coefficient a in COP regression (–)	100	100	100
Exponent b in COP regression (–)	1.6	1.6	1.6
Coefficient c in COP regression (–)	−0.08	−0.08	−0.08
Coefficient d in COP regression (–)	6	7	8
Heating temp. from heat pump ($T_{s,h}$) (°C)	30	45	60
Cooling temp. from heat pump ($T_{s,c}$) (°C)		$T_{aq} - \Delta T_g R_T$	

system. Calculating the energy supplied by a balanced GWHC system is a special case of the more general calculation for an ATES system with $T_r = 0$. Consequently, for a given system specification in terms of capacity, number of boreholes, groundwater flow rate and injection temperatures, it is straightforward to compare electricity demand and carbon emissions for ATES and GWHC operation using Eqs. (16), (17) and (21).

A Monte-Carlo approach with the parameter value ranges shown in Table 3 was used to estimate the electricity consumption and CO_2 emissions per unit thermal energy delivered by ATES and GWHC systems utilising the same aquifer, via the same boreholes, and supplying the same building-side infrastructure. GWHC systems were modelled by setting $T_r = 0$ and assuming the heat pump is required to change the temperature from the ambient aquifer temperature to the desired supply temperature for both heating and cooling.

The CO_2 emissions per unit energy supplied were calculated from $E_{e,t}$ using published data (Fig. 3A). For comparison, we also report the electricity consumption and CO_2 emissions per unit thermal energy delivered by air source heat pumps (ASHP) [35,39] as these are the most commonly installed competing technology in the UK to supply low carbon heating and cooling [2,40]. Other technologies, such as hydrogen, are pre-commercial and were not addressed here.

3. Current status of ATES in the UK

We have identified eleven currently active ATES deployments in the UK, with one further installation at the permitting stage (Table 4). All active systems are located in England; nine are in London, one is in Brighton and one is in Manchester (Fig. 4). Not all UK deployments were identified in the worldwide review of ATES undertaken by [8] and some uni-directional schemes were mis-identified as ATES systems.

The first ATES system was deployed in the UK in 2006 at a residential development in West London (Table 4). Since then, there has been on average fewer than one new system installed per year. Growth of the technology in the UK has therefore been very slow. All but one of the operational ATES installations utilise the Chalk aquifer in London or Brighton; the system in Manchester utilises the Triassic Sherwood Sandstone aquifer. As we show later, the current focus of ATES deployments in the London area is not representative of the geographical potential of ATES in the UK.

Buildings that have been equipped with ATES systems in the UK are mostly large, new-build residential developments, but also include a shopping centre, offices/work space and part of a museum. Most installations deliver <1 MW_{th} heating and cooling via a single well doublet and are bivalent, supplying part of the heating/cooling demand. In most cases, peak cooling demand is larger than peak heating demand, highlighting the importance of supplying low carbon cooling as well as heating. One of the largest current ATES systems in the UK supplies heating and cooling to the Wandsworth Riverside Quarter residential development. We analyse this system in more detail in the next section. We also discuss, in a later section, some UK installations in which problems with design and operation have caused sub-optimal performance. These installations are reportedly anonymously by request of the operator.

4. Wandsworth Riverside Quarter: Performance analysis of an example ATES installation in the UK

Experience of ATES installations elsewhere, especially in The Netherlands, has shown that monitoring of operational systems provides essential data to understand and quantify performance. Analysis of well flowrates and wellhead temperature data allows ATES system efficiency and sustainability to be assessed. Sharing the results is important to leverage experience from existing projects, to inform planning and permitting decisions for future projects, and raise awareness of ATES installations.

Here, we report a case study of the ATES system supplying the Wandsworth Riverside Quarter (WRQ) residential development in

Table 4
ATES deployments in the UK and design characteristics.

Project name	Date	Building type	Wells	Max licensed flowrate (m^3/h)	Peak load heating/cooling (kW_{th})
1. Westway Beacons	2006	Housing	2	25	250
2. Grosvenor Hill	2008	Housing	2	50	300/320
3. One New Change	2010	Shopping centre	2	40.5	600
4. National Maritime Museum	2011	Museum	2	46	300/350
5. Trafford Town Hall	2012	Offices	2	60	600
6. Riverside Quarter	2013	Housing	8	280	1800/2750
7. St James Riverlight	2015	Housing	8	240	1800/2900
8. Spring Mews Student Accommodation	2015	Housing	2	25	400/1204
9. Cockroft Building, University of Brighton	2016	University Building	2	99	703/546
10. Chelsea Barracks	2018	Housing	8	41.6	1062/650
11. City, University of London Law School	2019	University Building	2	72	600/590

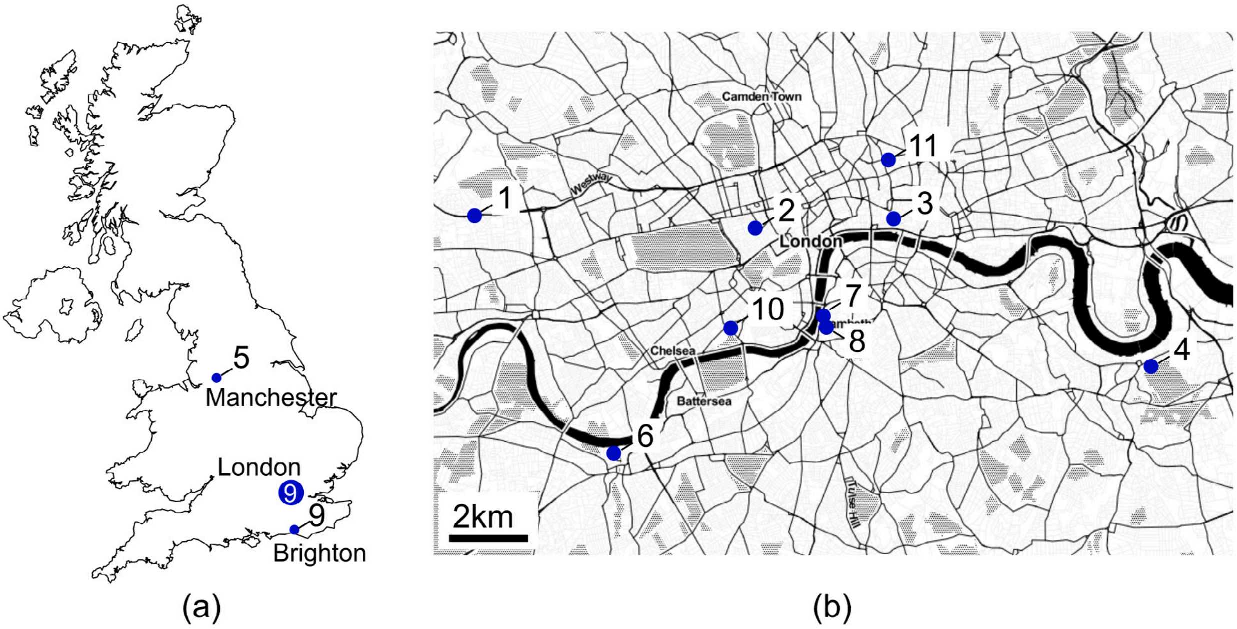

Fig. 4. (a) ATES deployments in the UK, indicated by blue circles. (b) Zoom in to the London area. Numbering corresponds to project numbers given in Table 4.

south-west London (Fig. 5). This multi-well ATES project, operating in the Chalk aquifer, serves as an example of the potential of ATES systems to provide sustainable, low carbon heating and cooling in the UK. It also has wider international significance because the hydrogeological properties of the Chalk aquifer are very different to those of aquifers that are typically targeted for ATES installations elsewhere. Groundwater flow in the Chalk occurs primarily through fractures; solid (unfractured) Chalk rock has high intergranular porosity but very low permeability so allows high storage but little flow of groundwater [41–43]. By contrast, most ATES systems, particularly those in the Netherlands, target sands and sandstone rock with high intergranular porosity and permeability which accommodates most of the groundwater storage and flow [27,31]. ATES deployments in the UK Chalk aquifer therefore provide important evidence for the efficiency and sustainability of ATES deployments in fractured aquifers.

4.1. Case study background and context

The energy system for WRQ was designed following the 'London Plan' operating at the time (see [44] for the current version) which promoted on-site generation of renewable energy and introduced minimum targets for the reduction of CO_2 emissions. The energy system at WRQ consists of an ATES deployment that provides space heating and cooling, coupled with gas boilers and a combined heat and power engine to provide hot water and supplementary space heating. Supplementary space cooling is provided by dry air coolers. The space heating and cooling system is designed to redistribute waste heat or cool around the development via the heat pumps before calling on new supply from the aquifer [45].

The ATES system consists of 8 wells: 4 cold wells and 4 warm wells (Fig. 5b). The wells are drilled to maximum depths between 113 and 143 mbgl (metres below ground level) [46]. The wells target the upper part of the Chalk, which is present from 79 mbgl depth at all 8 wells. The Chalk is overlain by mudstones and siltstones of the London Clay formation that acts as an aquitard and confines the Chalk aquifer; borehole logging data suggest the Thanet Sands, and Woolwich and Reading Beds, that often overlie the Chalk [47], are locally absent. The maximum licensed abstraction flowrate is 280 m^3/h and the designed maximum capacity of the system is 1.8 MW_{th} heating and 2.7 MW_{th} cooling (Table 4). The groundwater wells are coupled with two heat pumps which can provide both heating and cooling. Flow logging after the wells were drilled showed that the majority of the flow into and out of the wells occurs in the upper 15 m of the Chalk, with significant flow between 80–82 mbgl, consistent with numerous previous studies that have identified a high permeability interval at the top of the Chalk aquifer in London [48,49].

4.2. Wandsworth Riverside Quarter ATES: System performance

The ATES system at WRQ has been operating since 2013 and hourly total flowrate and temperature monitoring data have been provided for a period extending from 2015–2022, allowing the performance of the system to be assessed. The temperatures and production flowrates for the warm and cold wells over time are shown in Fig. 6. For visualisation

Fig. 5. (a) Photograph of Wandsworth Riverside Quarter. (b) Aerial image of the site; well locations shown by blue and red circles for cold and warm wells respectively. *Source:* Modified from [46].

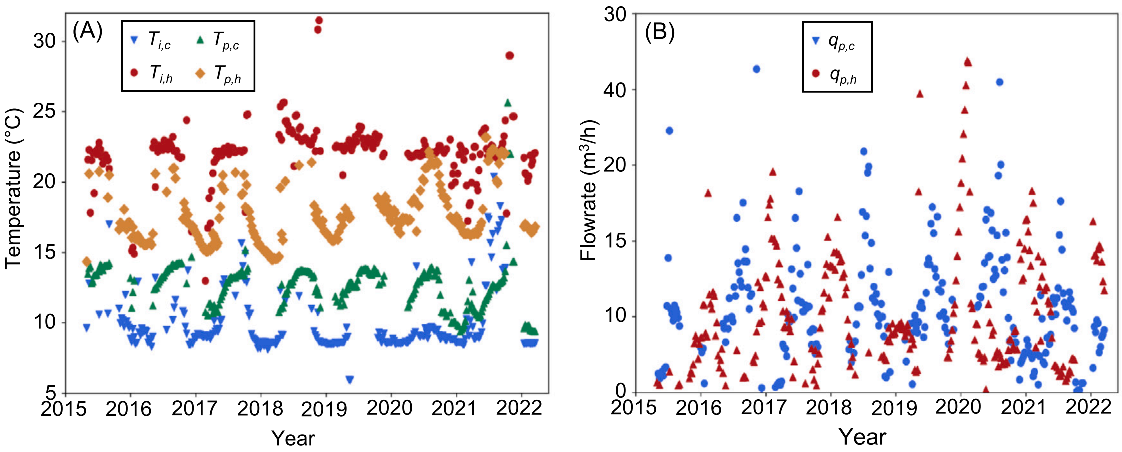

Fig. 6. Weekly averaged (a) injection (T_i) and production (T_p) temperatures and (b) production flowrates (q_p) for the warm (h) and cold (c) wells over the 2015–2022 monitoring period.

purposes, flowrates and temperatures were averaged on a weekly basis, with temperature weighted by the corresponding flowrate.

The cyclic behaviour that is expected of an operating ATES system [12] can be observed. In winter, groundwater is produced via the warm wells, and its temperature gradually decreases as cooler water is produced that was stored earlier in the previous cycle. After delivering its heat, the cooled groundwater is injected via the cold wells at a relatively constant temperature. Fluctuations in injection temperature correspond to variations in outside and inside building temperatures and the corresponding load on the heat pumps. In the summer, groundwater is produced via the cold wells, and its temperature gradually increases as warmer water is produced that was stored earlier in the previous cycle. After delivering its cool, the warmed groundwater is injected via the warm wells at a relatively constant temperature. Production flowrates from the warm wells peak in the winter months and *vice-versa*. A summary of the monitoring data is given in Table 5.

Table 5

Summary of monitored data from the Wandsworth Riverside Quarter ATES system. The average production flowrates only include non-zero values (i.e. they represent the average production flowrate when the wells are actively producing). Total values are reported for the available monitoring data extending from 2015 to 2022. Annual values are the average over the monitoring period.

Monitored data	Cold wells	Warm wells
Average injection temperature (°C)	9.8	22.2
Average production temperature (°C)	12.6	17.6
Average production flowrate (m^3 h^{-1})	14.4	13.8
Annual production hours/days	3243/135	3542/148
Annual volume produced (m^3)	46 634	48 921
Annual energy produced (MWh)	508	424
Total production hours/days	22 314/930	24 375/1016
Total volume produced (m^3)	320 842	336 581
Total energy produced (MWh)	3496	2918

The energy balance ratio EBR (Eq. (2)) is found to be 0.09 over the monitoring period, demonstrating that the system has maintained a close balance between heating and cooling loads. The energy extracted for cooling was approximately 20% more than the energy extracted for heating. The dry air coolers installed at WRQ could provide additional cold well recharge if the energy imbalance were to further increase. The volume balance ratio VBR (Eq. (4)) was calculated to be −0.03, which indicates that similar volumes of groundwater were used in cooling and heating modes. These data suggest that the system is sustainable.

Fig. 7a shows the annual thermal recovery (Eq. (5)) for the warm and cold wells over the 2015–2021 period; monitoring data from 2022 were not included as they do not span the entire year. The average thermal recovery of the cold wells (16%) is found to be lower than that of the warm wells (30%) over the period. As noted above, more energy was extracted during this period for cooling than heating, which could be a contributing factor to the lower T_r observed for the cold wells. The cold and warm wells show increasing thermal recovery over time which is expected in a correctly functioning ATES system: as the aquifer around the warm and cold wells gradually warms and cools respectively during operation, the temperature of the injected groundwater changes less during storage [9,50].

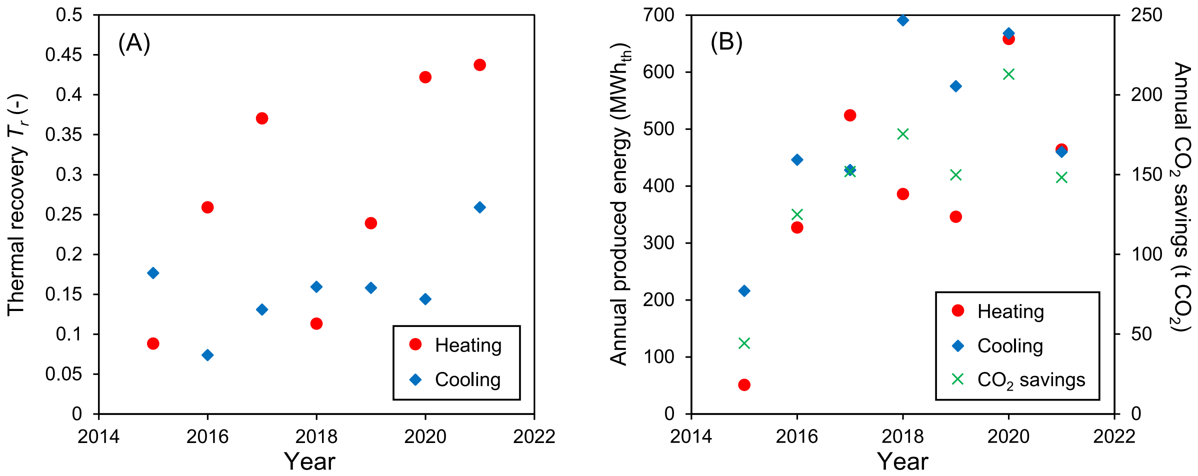

Fig. 7. (a) Thermal recovery (T_r) for the warm wells providing heating, and the cool wells providing cooling, for each year in the 2015–2021 period. Dashed lines indicate the trend for increasing recovery but are not intended to provide a close fit to the data. (b) Annual produced energy for heating and cooling for the 2015–2021 period and associated CO_2 saved, compared to natural gas based on CO_2 emissions for the 2020 UK energy mix (see Section 6).

After 9 years of operation, the thermal recovery for the system is lower than typically observed for ATES systems operating in less geologically complex aquifers such as the sands and sandstones utilised in The Netherlands [27,31]. As discussed above, these aquifers are less heterogeneous than the Chalk, in which flow occurs primarily within fractures with variable spatial distribution, aperture and connectivity [48,51]. Aquifer heterogeneity can significantly reduce the thermal efficiency of ATES systems [9,31]. At the WRQ site, flow likely occurs primarily within the upper few metres of the Chalk [48,49]. We have undertaken numerical modelling showing that this may cause significant lateral spreading of the thermal plumes (see [52] for further details) which have a ‘pancake’ geometry rather than the ‘cylinder’ geometry observed in a homogeneous aquifer (Fig. 8).

Lateral spreading of the plumes can reduce thermal recovery in two ways. First, a plume with ‘pancake’ geometry has a much larger surface to volume ratio, yielding higher conductive heat losses into the over- and underlying rock [30]. Second, lateral spreading increases the probability of thermal interference. We can define an ‘effective screen length’ in Eq. (1) which accounts for the limited vertical extent of inflow observed in the borehole flow logs at the site. As the effective screen length decreases, the thermal radius increases (Fig. 9). For effective screen length <1.5 m, the thermal radii for the wells at the WRQ site are estimated to be greater than the minimum separation between cold and warm wells (127 m), so the system would be at risk of short-circuiting (i.e. groundwater in the cold plume would be produced via the warm wells and *vice-versa*). For effective screen length <5 m, the thermal plumes would likely interfere as the thermal radii would be lower than half the minimum well spacing. To match Dutch guidelines of well spacing $>3R_{th}$, the effective screen length at the WRQ site must be >12 m. Flow logging suggests inflow over a ca. 2 m interval in all wells, so thermal interference may be occurring.

Low thermal recovery could also be caused by slow heating and cooling of the rock between flowing fractures [53], or by ambient groundwater flow, which can displace the warm and cold plumes away from the boreholes and lead to lower recovery of stored heat [54]. To further determine controls on thermal recovery requires a calibrated numerical model of flow and heat transport within the aquifer, the development of which is beyond the scope of this study. However, as discussed previously, low thermal recovery does not mean that an ATES system fails to deliver low carbon heating and cooling. The energy delivered from the aquifer by a balanced ATES system with zero thermal recovery is equivalent to the energy delivered by a balanced GSHC system.

4.3. Wandsworth Riverside Quarter ATES: Delivery of low carbon heating and cooling

The annual low carbon energy for heating and cooling delivered by the WRQ ATES system is shown in Fig. 7b. Consistent with the increasing thermal recovery factor (Fig. 7a), the energy delivered gradually increases for both warm and cold wells. The average annual energy supplied for cooling (494 MWh$_{th}$) is larger than that supplied for heating (391 MWh$_{th}$), consistent with the EBR calculated above. It should be noted that the energy supplied is smaller than that typically delivered by systems of similar scale, which is of order 1–2 GWh$_{th}$/yr [e.g. 8,12]. Relatively low energy supply is consistent with the relatively low operational flowrates compared to the licensed capacity (compare Fig. 6 and Table 4). The temperature drop across the heat exchangers is typical of ATES systems (Table 5), consistent with efficient heat and cool exchange with the building side, but the low flowrates restrict the power that is supplied. Low energy delivery may be due to low occupancy, coupled with efficient redistribution of heat and cool around the buildings via the heat pumps without drawing on heat and cool from the aquifer [45].

Using our estimated CO_2 emissions for ATES (see Section 6), the annual emissions savings from the WRQ system can be calculated, taking natural gas as a reference energy source (Fig. 7b). From the 2nd year of operation, the ATES system always saves >100 tonnes of CO_2 each year. Given the trend of increasing thermal recovery factor (Fig. 7a), and as UK electricity generation continues to move to renewable sources (see Section 6), the CO_2 savings from the WRQ ATES system will further increase. Successful installation and operation of the WRQ ATES system demonstrates the feasibility of ATES deployments in the Chalk aquifer. Calculated metrics indicate that the system is sustainable, maintaining balanced heating and cooling energy storage and extraction.

5. Potential for ATES in the UK

5.1. Climate and aquifer suitability

The previous section has demonstrated that ATES systems can operate successfully in the UK but are few in number and largely located in London. As discussed previously, the basic requirements for ATES deployment are a seasonal climate with distinct periods of heating and cooling demand, and the availability of a suitable storage aquifer. With respect to the first requirement, the temperate UK climate is well suited to ATES (Fig. 10). Seasonal temperature variations are observed across

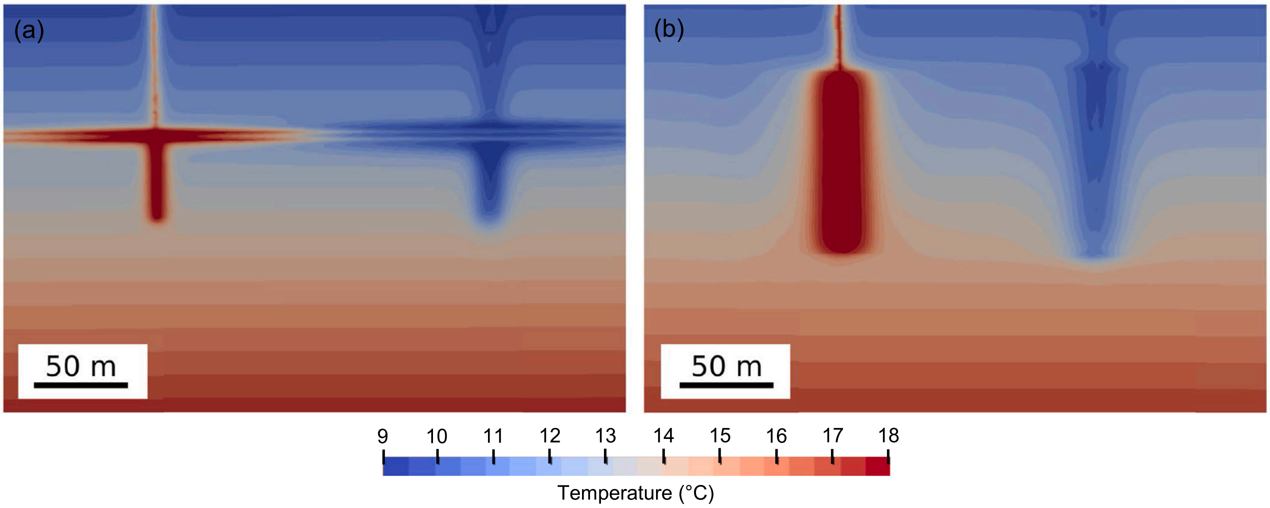

Fig. 8. Snapshot of the temperature field in a 2D section through a 3D numerical simulation of ATES system operation using a well doublet in (a) the heterogeneous Chalk aquifer and (b) a homogeneous aquifer.
Source: Modified from [9,52].

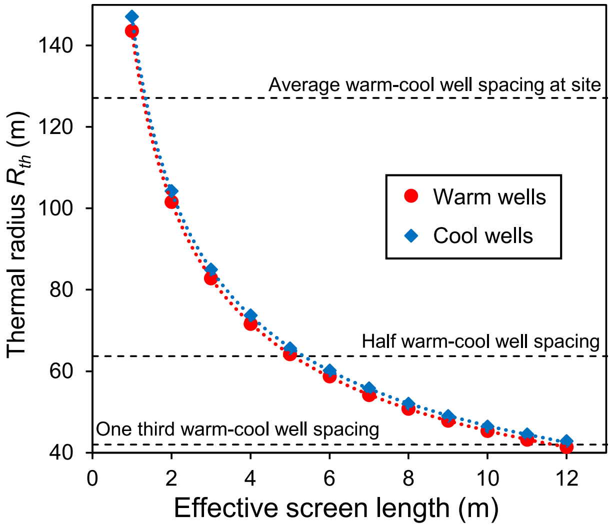

Fig. 9. Thermal radii for cold and warm wells at the WRQ site as a function of effective screen length, calculated using the average annual volume of groundwater injected at the warm and cold wells. The Chalk aquifer porosity was assumed to be 0.314 [42]. The heat capacity of the Chalk was taken to be 890 J/kg K and the density to be 2800 kg/m^3 [43]. The horizontal dashed lines indicate the average spacing between warm and cold wells at the site, half the site well spacing and one third of the site well spacing.

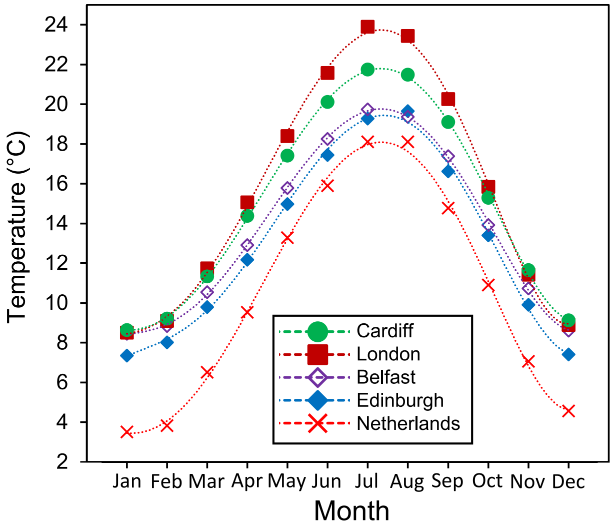

Fig. 10. Mean average temperatures in UK capital cities and the Netherlands over the period 1991–2020 [55,56].

the UK that are similar to those of neighbouring countries in which ATES systems are widely deployed. The restricted use of ATES in the UK to date is not related to climatic conditions.

With respect to the second requirement, the UK has a long tradition of extracting groundwater for drinking, agricultural and industrial use from several principal and numerous secondary aquifers that are geographically widespread and located at suitable depth [48,60]. Principal aquifers in the UK have high porosity (typically of order 0.2–0.4) and permeability (typically of order 10^{-14}–10^{-10} m^2 (1 mD–10 D)), providing a high level of groundwater storage and transmission and supporting water supply on a strategic scale [42,48]. Secondary aquifers are porous and permeable rock layers capable of supporting water supply at a local rather than strategic scale, or lower permeability layers which may store and yield limited amounts of groundwater due to localised features such as fissures or thin permeable horizons and weathering. The most important principal UK aquifers are the Carboniferous limestone, the Magnesian limestone, the Permo-Triassic sandstones, the Oolites, the Corallian, the Greensand and the Chalk [48].

Previous studies have developed maps of aquifer suitability for ATES in Spain and Germany, characterised in terms of properties such as aquifer productivity (or yield) and depth, groundwater chemistry, and ambient groundwater flow [61,62]. In the UK, previous work has assessed aquifer suitability and availability for GWHP deployments [57]. A screening tool is available to classify the subsurface as more or less suitable for such open-loop systems with capacities >100 kW$_{th}$. The tool considers aquifer productivity and depth, groundwater chemistry and protected areas. Only aquifers shallower than 300 m below ground level are considered for these systems, as drilling deeper would typically be uneconomic [57]. The tool was initially developed for England and Wales [57] and then further extended to Northern Ireland [58], although in Northern Ireland it includes only aquifers present at the surface, thus significantly limiting the available area. Many aquifers suitable for ATES are confined by overlying rock units.

There is no comparable tool for ATES in the UK, so we have used the existing open-loop GWHP tool and additional published sources to

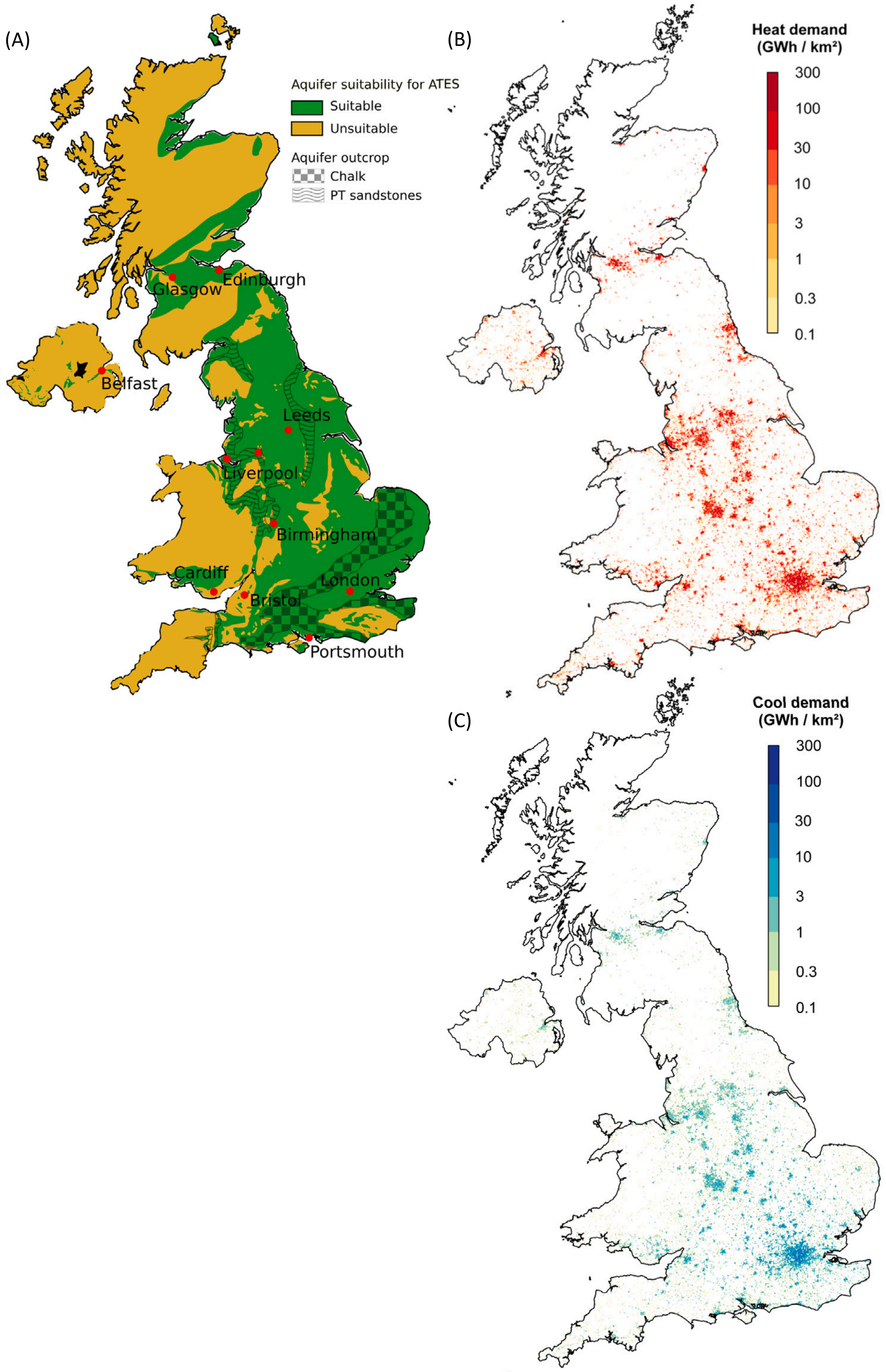

Fig. 11. Spatial distribution of aquifers suitable for ATES, and heating and cooling demand, across the UK. (a) Aquifer map compiled using data from the open-loop ground source heating/cooling screening tool for England and Wales [57], from [58] for Northern Ireland and from [59] for Scotland. Green shading indicates areas with potential for ATES. The outcrop areas of the Chalk and Permo-Triassic (PT) sandstone aquifers are shown in overlay. Major UK cities are indicated by red circles. (b) Average total annual heating demand from buildings (space heating plus domestic hot water) over the period 2010–2022; (c) Average total annual cooling demand from buildings over the same period. Plots (b) and (c) compiled using data from [34], with demand variability from year to year derived using the Demand.ninja model [20].

make an initial estimate of the geographic distribution of UK aquifers suitable for ATES (Fig. 11) [57–59]. The potential for ATES in Scotland is assessed here only by the presence or absence of Carboniferous and Devonian sandstones which, although classed as secondary aquifers, still offer borehole flowrates that could be sufficient for ATES [59]. It can be observed that a large proportion of the UK has aquifers available that may be suitable for ATES deployment. A more detailed local assessment is required of aquifer properties, groundwater flow and chemistry, existing groundwater usage and other potential barriers to deployment to determine whether the aquifer is suitable and available for ATES at a particular location. Note that, where no suitable aquifer is present, closed-loop geothermal technologies such as BTES could be deployed instead.

Aquifer availability and suitability must also be aligned with demand for heating and cooling. In contrast to fuels, heat cannot be transported over large distances. Many major UK urban centres with high heating and cooling demand are co-located with aquifers which are used for water supply and are suitable for ATES deployment (Fig. 11). For example, as discussed above, London is underlain by the Chalk principal aquifer [48,63], while Liverpool, Manchester, Birmingham and Belfast are all underlain by the Permo-Triassic sandstone principal aquifer. Edinburgh and Glasgow are underlain by Carboniferous sandstones. The UK has high potential for widespread deployment of ATES and the current low uptake is not because of unsuitable climate or lack of available aquifers.

5.2. Proportion of UK heating and cooling demand that could be supplied using ATES

The results of our Monte-Carlo analysis show that ATES could supply up to 190 $GWh_{th}/yr/km^2$ of heating, with a mode of 25 $GWh_{th}/yr/km^2$ (Fig. 12a). The distribution is approximately log-normal and is best fit using a gamma distribution (see caption of Fig. 12 for details). Potential cooling supply is smaller because there is no contribution from the heat pump, ranging up to 150 $GWh_{th}/yr/km^2$ with a mode of 20 $GWh_{th}/yr/km^2$ (Fig. 12b). Uncertainty in heating and cooling supply is dominantly controlled by the well screen length, the fraction of available aquifer and the groundwater temperature change. The impact of the other uncertain parameters listed in Table 2 is negligible.

Published estimates for the power density of ATES systems are rare; [32] obtained values in the range 11–30 $GWh_{th}/yr/km^2$ from numerical models of the aquifer beneath Freiburg in Germany. High ambient groundwater velocities in the aquifer yield low thermal recovery (of order 0.1–0.6 in their study) because the warm and cold plumes are displaced from the storage wells. The higher power densities obtained from our Monte-Carlo analysis correspond to scenarios with higher thermal recovery (Table 2), consistent with monitoring data from operating systems (see Appendix A). Assuming borehole flow rates in the range 20–100 m^3/hr with a most likely value of 50 m^3/h (Table 4; see also [8,11,12,41,48,49,51,57,60,64,65]), the modal number of warm and cold boreholes required to deliver the heating and cooling energy per km^2 shown in (Fig. 12a,b) is 16, with 80% of trials requiring fewer than 50 boreholes of each type. Larger borehole numbers correspond to trials with a large available aquifer area, long screen length, small groundwater temperature change and low borehole flowrates i.e. cases with large potential for ATES but where individual wells deliver small heating or cooling power. Drilling such a large number of boreholes to deliver large capacity heating and cooling is unlikely to be economic; moreover, borehole locations would need to be carefully planned, grouping warm and cold wells to avoid negative thermal interference [65]. Omitting these cases from the analysis reported below has negligible impact on the results.

These probabilistic estimates of heating and cooling supply per km^2 (Fig. 12a,b) were combined with heating and cooling demand data mapped onto the same km^2 grid (Fig. 11b,c) (see Methods). Summing the demand data yields a total of 515 TWh_{th} heating and 79 TWh_{th} cooling demand (in terms of thermal energy delivered) on average each year, with the spread around the mean shown in (Fig. 12c,d). Comparison of potential ATES supply (Fig. 12a,b) and local average demand (Fig. 11b,c) shows that supply will often substantially exceed local demand; however, in urban areas with high population density, demand may exceed ATES supply even when a suitable aquifer is present [32].

Summing over the potential heating and cooling energy supplied in each km^2 yields the total annual heating and cooling (Fig. 13a,b), and the percentage of total current demand (Fig. 13c,d), that could be supplied by ATES. The resulting distributions are approximately normal, consistent with the central limit theorem and the fact that the distributions are obtained by summing over many independent random variables (one for each km^2 where an aquifer is present, totalling ca. 32,000 values), each of which is drawn from an identical distribution [33].

Annual heating supply, limited by the local demand in each km^2, ranges from 312 TWh_{th}/yr to 320 TWh_{th}/yr, with a mean = mode of 316 TWh_{th}/yr (Fig. 13a) corresponding to ca. 61.3% of UK annual heating demand (Fig. 13c). Annual cooling supply, limited by local demand in each km^2, ranges from 61.8 TWh_{th}/yr to 63.2 TWh/yr, with a mean = mode of 62.5 TWh_{th}/yr (Fig. 13a) corresponding to ca. 79% of UK annual cooling demand (Fig. 13d).

It is important to note that ATES could meet a much larger cooling demand than our estimate suggests: potential cooling supply per km^2 is of similar magnitude to potential heating supply (compare Fig. 12a and b); total potential cooling supply is restricted by current low demand owing to the lack of installed capacity, rather than aquifer availability or low supply per km^2 where an aquifer is present. Future cooling demand is predicted to increase in response to the warming climate [18,19], so the capacity of ATES to supply cooling will become increasingly important. Despite its large potential, ATES in the UK currently supplies $<0.01\%$ of national heating demand and $<0.5\%$ of cooling demand.

The spread of estimated heating and cooling demand that could be supplied by ATES is surprisingly narrow given the broad range of predicted values of annual heating and cooling supply per km^2 (Fig. 12a,b). Most locations in the UK have heating and cooling demand that is well below the modal estimated value that could be supplied by ATES, so the main criteria for supply is aquifer availability. If an aquifer is available, ATES can meet demand in most locations. Only in urban centres does heating and cooling demand match, or exceed, ATES supply. Consequently, uncertainty in supply in the relatively few and geographically restricted urban areas of the UK primarily controls the spread of estimated heating and cooling demand that could be supplied by ATES.

6. Decarbonisation potential of ATES in the UK

The results of our Monte-Carlo analysis show that ATES requires 0.06–0.36 kWh_e per kWh_{th} of heating delivered with a mode of 0.21 kWh_e/kWh_{th}, and 0.01–0.08 kWh_e/kWh_{th} of cooling delivered with a mode of 0.02 kWh_e/kWh_{th} (Fig. 14). The corresponding system COP (SCOP) ranges from 2.7 to 15, with a mode of 4.64 for heating, and from 12 to 165, with a mode of 40 for cooling (Fig. 15). The very low electricity consumption, and corresponding high SCOP of ATES for cooling, is a direct consequence of storing and re-using waste cool, which means that cooling can be provided directly without use of a heat pump. Uncertainty in predicted electricity consumption and SCOP for heating is primarily controlled by the temperature of the supply to the building, the heat pump COP, and the groundwater temperature change; uncertainty in predicted electricity consumption and SCOP for cooling is primarily controlled by the electrical energy for groundwater pumping, and the groundwater temperature change.

Equivalent GWHC systems require 0.16–0.45 kWh_e per kWh_{th} of heating delivered, with a mode of 0.23 kWh_e/kWh_{th}, and 0.01–0.2 kWh_e per kWh_{th} of cooling delivered, with a mode of 0.07 kWh_e/kWh_{th} (Fig. 14; see Fig. 16A for a direct comparison). The corresponding SCOP ranges from 1.5 to 8 with a mode of 4.08 for heating, and from 5 to 73 with a mode of 10 for cooling (Fig. 15). ATES therefore offers significantly lower electricity consumption and higher SCOP than equivalent GWHC: our Monte Carlo analysis shows that ATES offers a 7%–23% reduction in electricity consumption with a mode of 9% for heating; the corresponding increase in SCOP ranges from 7 to 30% with

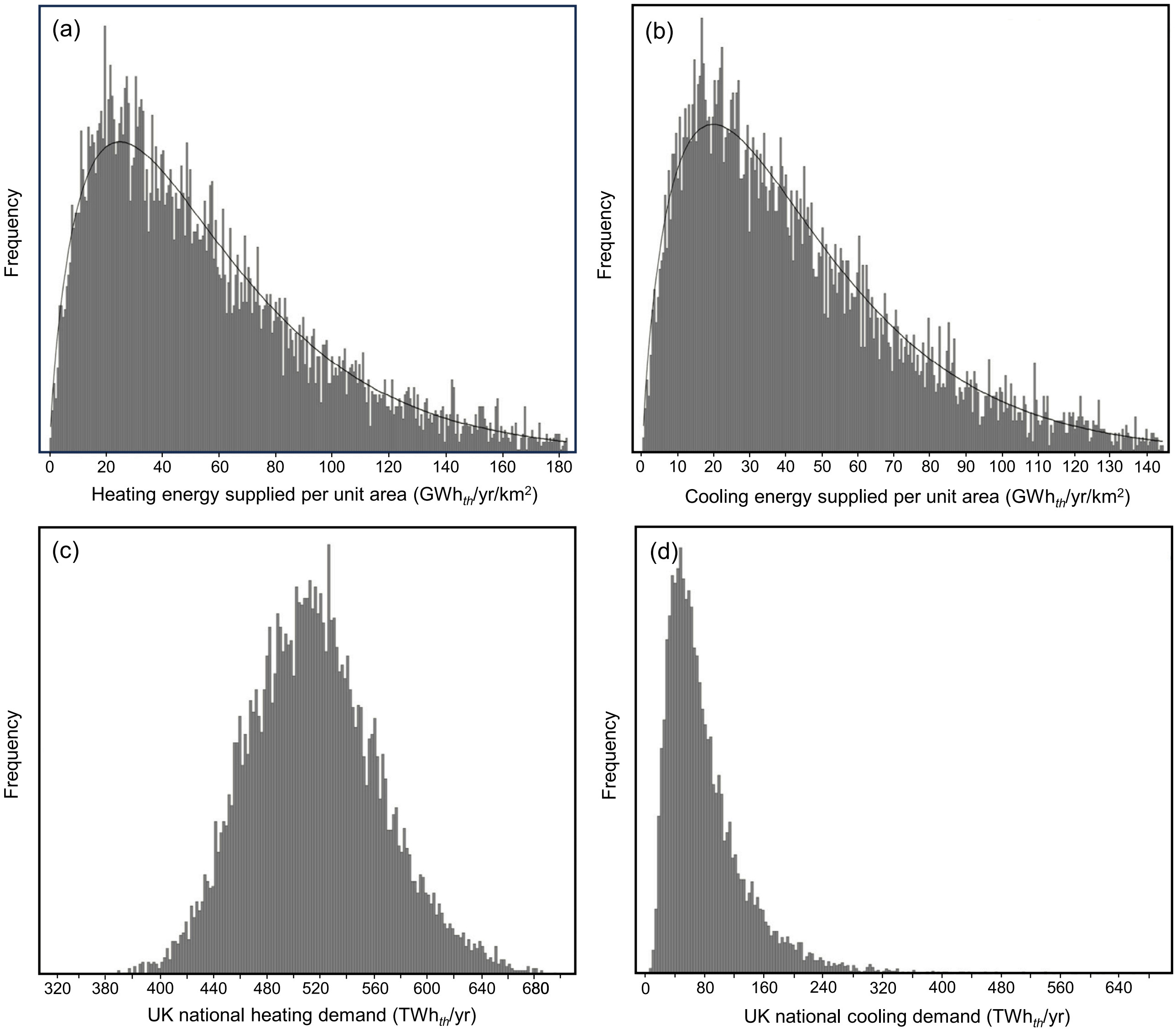

Fig. 12. Frequency plots showing the results of the Monte-Carlo analysis for annual heating and cooling supply per km^2, and total annual heating and cooling demand. (a) Annual heating that could be supplied by ATES per km^2 where an aquifer is present. (b) Annual cooling that could be supplied by ATES per km^2 where an aquifer is present. Best fit curves in (a) and (b) represent a gamma distribution with (a) location = 0.11, scale = 33.1 and shape = 1.75, and (b) location = 0.09, scale = 26.1 and shape = 1.75. (c) Total UK annual heating demand, accounting for annual variations over the period 2010–2022; the mode corresponds to the data shown in Fig. 11b. (d) Total UK annual cooling demand, accounting for annual variations over the same period; the mode corresponds to the data shown in Fig. 11c.

a mode of 10%. For cooling, ATES offers large reductions in electricity consumption: 19%–93% with a mode of 40%; the corresponding increase in SCOP ranges from 23 to 1000% with a mode of 134%. We note that SCOP may also be impacted by system design, operation and maintenance practices for both ATES and GWHC systems; here, we assume the systems are properly operated and maintained. As we show later, this is not always the case in current UK ATES installations. SCOP may be increased by optimal system design and operation, which is an area of active research [e.g. 29,65–67].

The decreased electricity consumption and higher SCOP for ATES as compared to GWHC translates to significant reductions in grid load and CO_2 emissions of ca. 13% for heating and 70% for cooling (Fig. 16B). We also predict significant reductions in grid load and CO_2 emissions compared to ASHP of 41% for heating and 94% for cooling. Widespread deployment of ATES in conjunction with decarbonisation of UK electricity generation could deliver heating with a carbon intensity that is 95% lower than the present day by 2030, with 41% lower grid demand than ASHP, and supply the UK's rapidly increasing demand for cooling with almost zero operational CO_2 emissions. Note that literature data for CO_2 emissions from ATES and GWHC systems are higher than those reported here, because they are calculated for an energy mix with a higher carbon intensity, and also include upstream CO_2 emissions [68]; future work will focus on life-cycle analysis of the CO_2 emissions from ATES deployments in the UK.

7. Challenges to widespread uptake of ATES in the UK

The UK is currently in the emerging market phase for ATES [8]. The currently operating UK ATES systems can be classified as 'demonstrator projects' which could be used to promote further uptake of ATES. Previous studies have identified barriers to widespread uptake of ATES in emerging markets such as the UK [8,22,69,70] and we summarise the key findings of these studies in Table 6. In researching current UK ATES deployments, we encountered all of these challenges, but focus here on a number of specific issues that have (i) impacted some operational UK systems such that they may not be used as demonstrator projects, and (ii) distinguish UK installations from those in the Netherlands, which offers the most obvious international example of large-scale

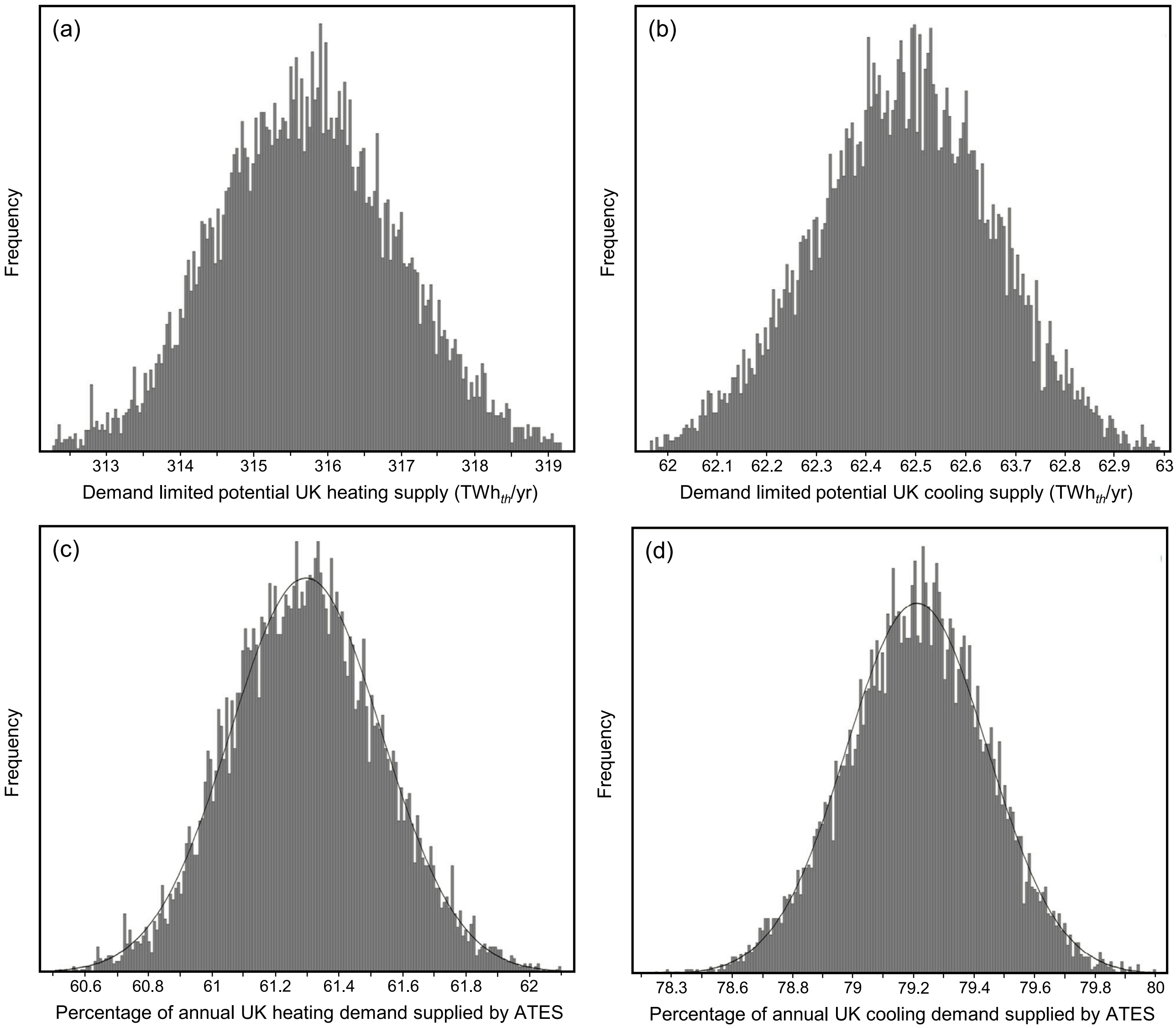

Fig. 13. Frequency plots showing the results of the Monte-Carlo analysis for total potential UK heating and cooling supply and the proportion of demand that could be met currently by ATES. (a) Annual heating that could be supplied by ATES in the UK, limited by demand. (b) Annual cooling that could be supplied by ATES in the UK, limited by demand. (c) Percentage of UK annual heating demand that could be supplied by ATES. (d) Percentage of UK annual cooling demand that could be supplied by ATES. Best fit curves in (c) and (d) represent a normal distribution with (c) mean = 61.3%, standard deviation = 0.24, and (d) mean = 79.2%, standard deviation = 0.23.

technology deployment. We report some anonymised UK installations in which problems with design and operation have caused sub-optimal performance and have engaged with the system operators to provide remedial solutions where required. There are strong parallels between the current status of ATES in the UK, and the status of domestic heat pumps a decade ago. Early UK trials of ASHP and GSHP revealed numerous problems and the average COP they achieved was far lower than in Germany, where the technology at the time was more mature [35].

7.1. Energy balance

A key requirement for a sustainable ATES system is to ensure balanced storage and extraction of heat and cool in the aquifer. Energy balance avoids changes in aquifer temperature that reduce system efficiency and may ultimately make the system unviable without remedial action [70]. We have identified at least one UK ATES system that has supplied higher cooling than heating since installation, resulting in excess waste heat injection into the aquifer. The temperature of groundwater produced at the cool well is now higher than the initial ambient groundwater temperature, indicating that there has been significant

Table 6
Key barriers to ATES uptake in immature markets, as identified by [8,69,70].

Barrier type	Description
Financial barriers	• Larger initial investment compared to conventional technologies • Low price of fossil fuels
Legislative barriers	• Long and/or complex permitting procedures • Lack of regulative framework for permitting • Lack of incentives for installation • Lack of awareness among policymakers
Technical barriers	• Lack of awareness by developers • Lack of technology know-how • Unfamiliarity with subsurface • Uncertainty in subsurface response
Societal barriers	• Lack of public awareness • Negative public perception of subsurface uses

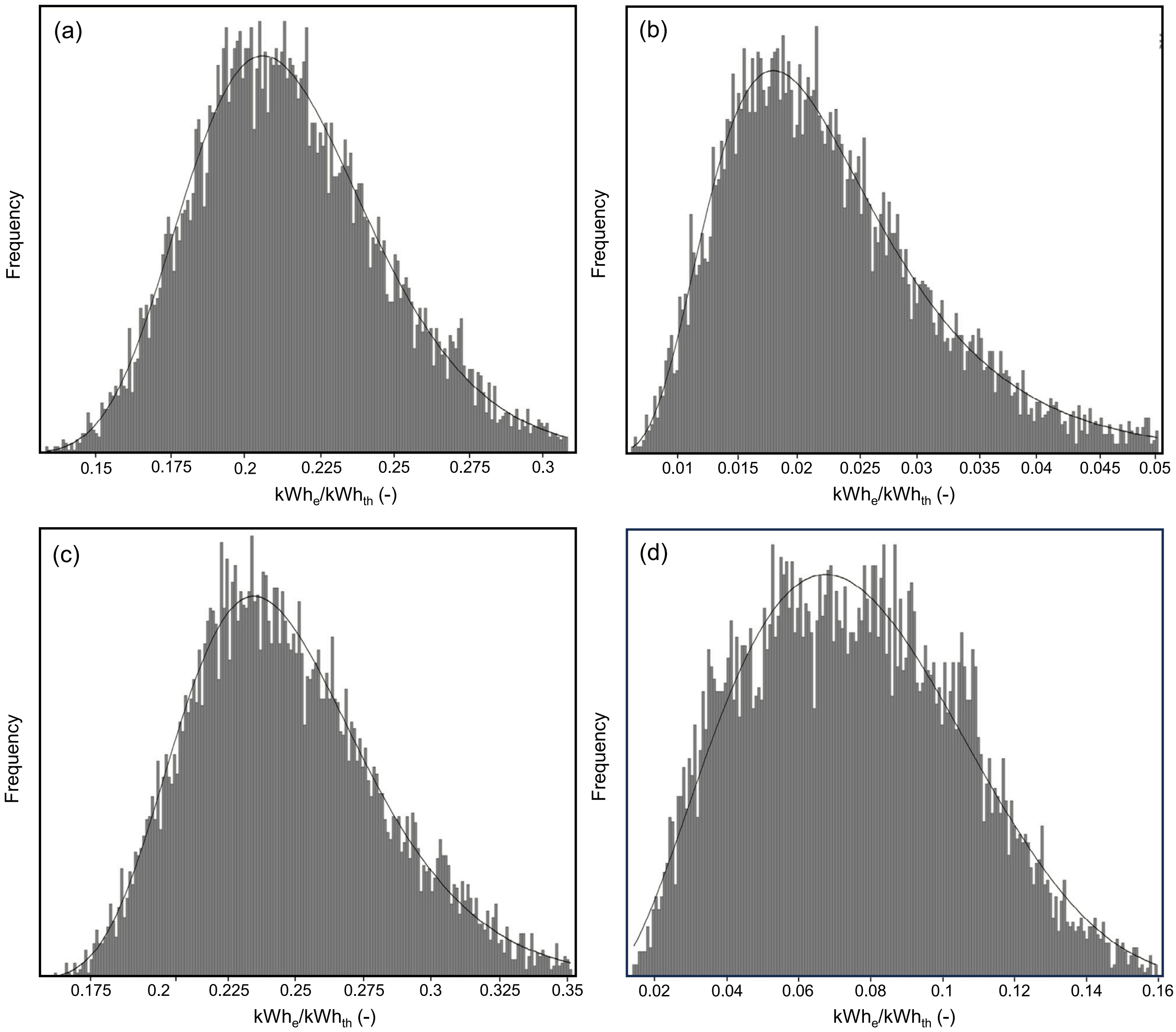

Fig. 14. Frequency plots showing the results of the Monte-Carlo analysis for electricity consumption per unit thermal energy delivered by (a) ATES supplying heating; (b) ATES supplying cooling; (c) GWHC supplying heating, and (d) GWHC supplying cooling. Best fit curves represent log-normal distributions with (a) mode = 0.21 kWh$_e$/kWh$_{th}$; (b) mode = 0.02 kWh$_e$/kWh$_{th}$; (c) mode = 0.23 kWh$_e$/kWh$_{th}$, and (d) mode = 0.07 kWh$_e$/kWh$_{th}$.

warming of the aquifer around the cool well. The system now operates almost exclusively in cooling mode, dumping waste heat via the warm well and consuming increasing electrical power in the heat pump to deliver the required cooling.

The negative impact of imbalance on system performance may be accelerated in the heterogeneous storage aquifers typical of the UK because the thermal plumes around the warm and cool wells spread laterally over larger distances as compared to a homogeneous aquifer (Fig. 8). Consequently, any imbalance will more rapidly interfere with production. In the ATES system described above, we hypothesise that the system imbalance is coupled with rapid migration of the warm plume to the cold well, possibly along a fault. However, the available data are at present insufficient to confirm this hypothesis

Extensive international experience confirms that energy balance is essential to ensure that ATES is sustainable. In some countries, notably the Netherlands, energy balance is a requirement for permitting [71]. Enforcing energy balance requires monitoring of injection and production flowrates and temperatures, along with interpretation of the data to calculate the energy balance ratio. These monitoring data also allow early identification of any problems with system operation, such as groundwater contamination due to the injection and production of fluids into and from the aquifer [e.g. 72]. Proper monitoring, maintenance, and mitigation measures are essential to mitigate such risks.

Enforcing energy balance requires ATES systems to be specifically identified in regulatory databases, and regular collection and interpretation of monitoring data. As discussed earlier, ATES systems are currently difficult to distinguish from GWHC and GWHP systems in UK databases. Our experience of ATES systems operating in the UK has shown that adequate monitoring equipment is not always present. For example, we have encountered systems with only recently installed temperature monitoring, and systems equipped with only unidirectional flowmeters, so total injected/abstracted volumes are measured, but not whether production is from the warm or cold wells. Note that energy imbalance can also have a negative impact on GWHC systems: consistent excess injection of waste heat or cool creates a large waste plume that can spread to the production well(s) unless removed by groundwater flow. GWHP systems that supply only heating or cooling are inherently imbalanced.

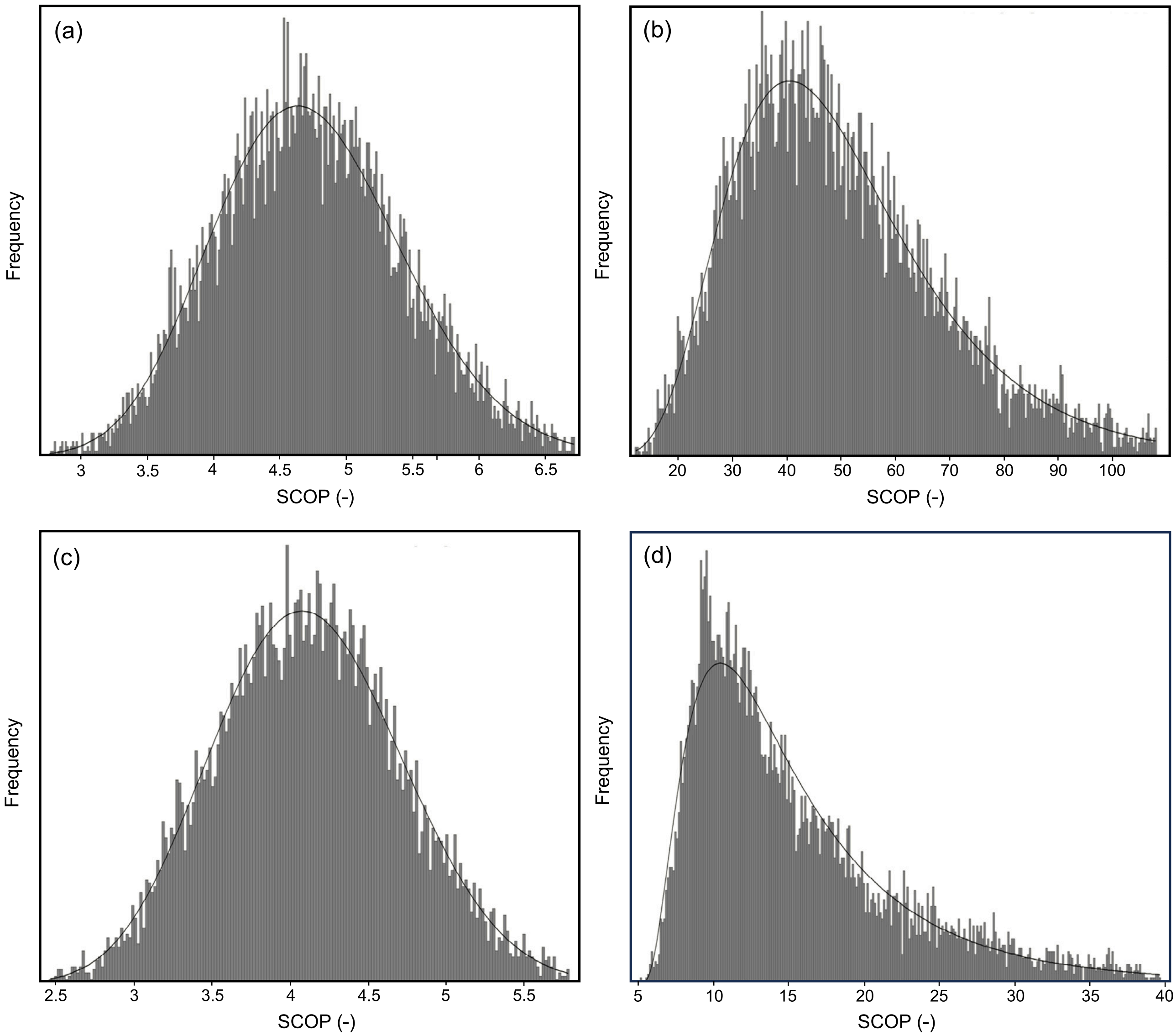

Fig. 15. Frequency plots showing the results of the Monte-Carlo analysis for seasonal COP of (a) ATES supplying heating; (b) ATES supplying cooling; (c) GWHC supplying heating, and (d) GWHC supplying cooling. Best fit curves for heating in (a) and (c) represent beta distributions; best fit curves for cooling in (b) and (d) represent log-normal distributions, with (a) mode = 4.64; (b) mode = 40.4; (c) mode = 4.08, and (d) mode = 10.4.

7.2. Geological heterogeneity and system design

Geological heterogeneity has been shown to significantly influence groundwater flow paths and therefore the shape and extent of thermal plumes (Fig. 8) [9,65,73–75]. When designing ATES systems installed in heterogeneous aquifers, it is essential to characterise the presence of heterogeneity and quantify its impact on groundwater flow and plume development during storage. Systems designed without consideration of heterogeneity can suffer from lower than predicted performance and higher risk of interference with neighbouring installations [31]. Similar considerations pertain to the design of GWHC and GWHP systems.

The UK's principal aquifers, such as the Chalk and Permo-Triassic Sandstones, are characterised by significant geological heterogeneity [41,48,49,51,60,64] (e.g. Fig. 17). As discussed above, the Chalk aquifer comprises a high porosity, low permeability rock matrix containing fractures, joints and dissolution features with variable spatial distribution and connectivity which act as pathways for rapid groundwater flow. The Triassic Sherwood Sandstone Group comprises fluvial and aeolian sandstones, typically with high but spatially variable permeability [64], which are likely to be exploited as preferential pathways for groundwater flow and heat transport during ATES operation. These permeable sandstones are often interbedded with low permeability lithologies, such as lacustrine and channelised mudstones with varying lateral continuity, which act as barriers to flow [76]. Fractures may also be present at shallow depth which act as additional flowpaths, and faults may acts as barriers or conduits for flow. Although the heterogeneous nature of UK aquifers is well known, and despite the evidence for heterogeneous flow in appraisal tests, we have observed the use of numerical models that assume homogeneous behaviour to predict UK ATES system behaviour.

Unpredicted lateral spreading of thermal plumes may result in well placement that allows short-circuiting between wells, interference between wells, and interference with other groundwater use. These negative effects can be avoided or mitigated if the subsurface response to aquifer storage is properly characterised and modelled, and the system is engineered appropriately. For example, laterally offsetting warm and cold wells follows the Dutch approach, based on deployments in relatively homogeneous and thin (of order 10's m) aquifers (e.g. Fig. 9). Lateral offsetting is optimal in these aquifers because there is little lateral plume spread and restricted vertical space.

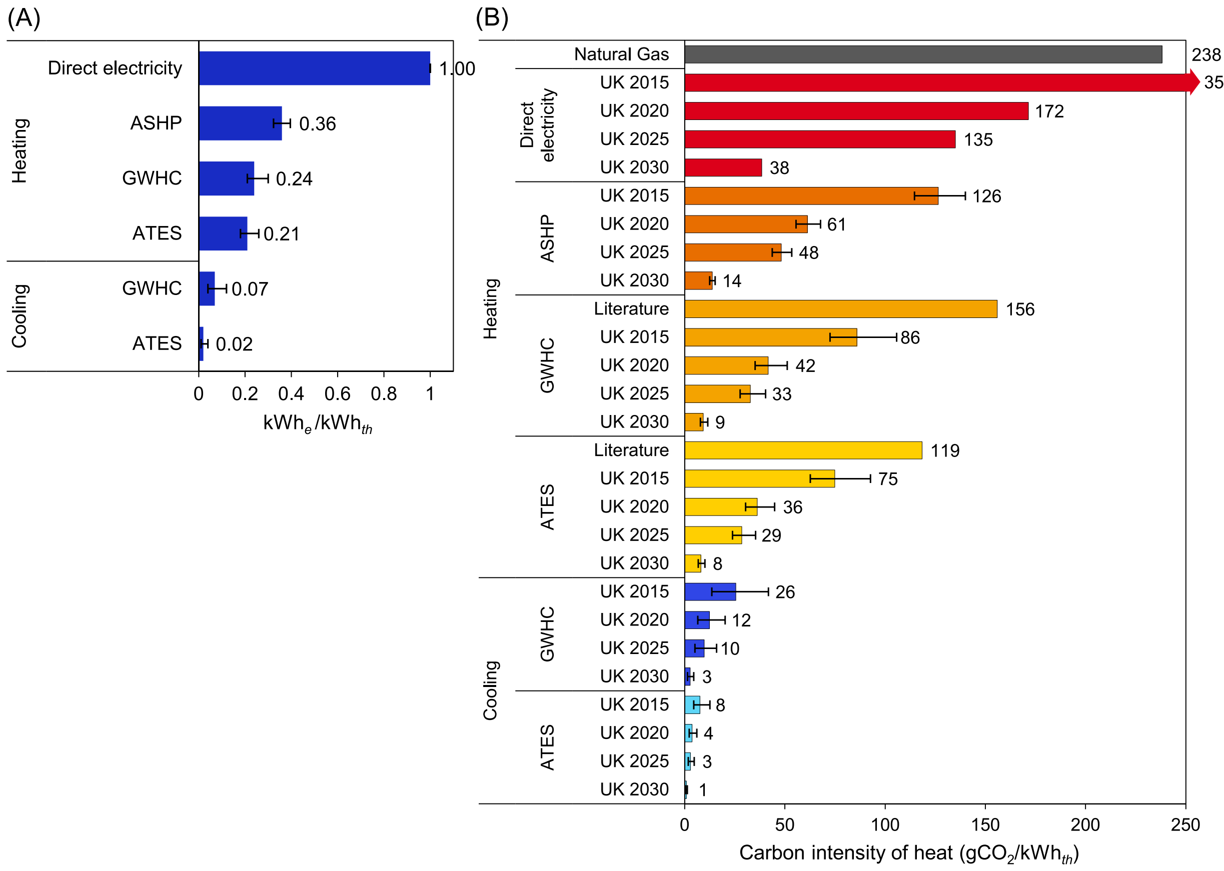

Fig. 16. Comparison of predicted (A) electrical energy required and (B) associated CO$_2$ emissions per unit heating or cooling energy supplied by ATES and GWHC. Also shown for comparison in (A) and (B) are data for air-source heat pumps (ASHP). Error bars represent the spread from the 10th to the 90th percentile. Literature data for GWHC and ATES systems from [68].

Aquifers in the UK are often thick (of order 100's m) and/or have restricted vertical permeability [41,48,49,51,60,64], in which case vertically offsetting the warm and cool plumes may yield increased storage efficiency and a smaller system footprint. Storage could be via separate, dedicated warm and cool boreholes operating at different depths, or via single boreholes injecting and abstracting both warm and cold groundwater via separate pipework within the borehole and screens at different depths (Fig. 18). We note the successful deployment of a uni-directional, open-loop GWHP cooling system in London based on this concept: groundwater at ambient temperature is abstracted at the top of the Chalk and used for cooling, and the waste heat (warmed groundwater) is injected deeper into the Chalk via the same borehole [77]. Ongoing research aims to characterise the development of thermal plumes in the heterogeneous Sherwood Sandstone and Chalk aquifers, using field test sites in Cheshire [78] and Berkshire [79], and apply the results to identify strategies for optimal system design and operation in these aquifer types.

7.3. Integration of ATES with building side heating/cooling systems

ATES systems integrate subsurface and surface components and their design, installation and operation requires collaboration between a wide range of technical and engineering experts typically working for different companies. After installation, it is essential that building services engineering teams clearly understand how the ATES system works and should be operated, that monitoring data are available, and that the data are regularly interpreted to confirm the system is working correctly, following the approaches used here for the WRQ system data. In the UK, communication has been particularly challenging as no domestic contractors currently install or manage ATES systems. Similar concerns pertain to the integration of other shallow geothermal technologies with building side infrastructure.

We have identified several UK installations in which problems with design and operation have caused suboptimal performance. The unbalanced system described in the previous section is included in this group. We have identified systems which have operated for several years without having been manually switched from heating to cooling mode when required, operating as GWHP systems with consequent impacts on plume formation and migration in the aquifer; we have also identified systems in which monitoring data suggest there is no clear temperature difference between groundwater produced from warm and cool wells or across the heat exchanger in either heating or cooling modes. It is not clear in this latter case whether any heat or cool is being delivered to the building by the ATES system. Bivalent operation means that shortfalls in heating or cooling delivered by the ATES system are met from other sources and may not be identified or diagnosed.

7.4. Technology awareness

Despite the large potential of ATES to deliver low carbon heating and cooling, there is a lack of awareness of the technology in the UK. In recent national policy documents identifying pathways to decarbonise heat in the UK [2,40], the importance of energy storage was highlighted but ATES was not identified as a technology which can deliver storage at scale. ATES is also not mentioned in local policy documents such as the London Plan. Regulatory bodies in the UK currently have no specific permitting policies for ATES. Buildings in the UK which currently use ATES for heating and cooling do not showcase the technology, which could help increase visibility. This general lack of awareness means that ATES is not considered as a technology to provide heating and cooling;

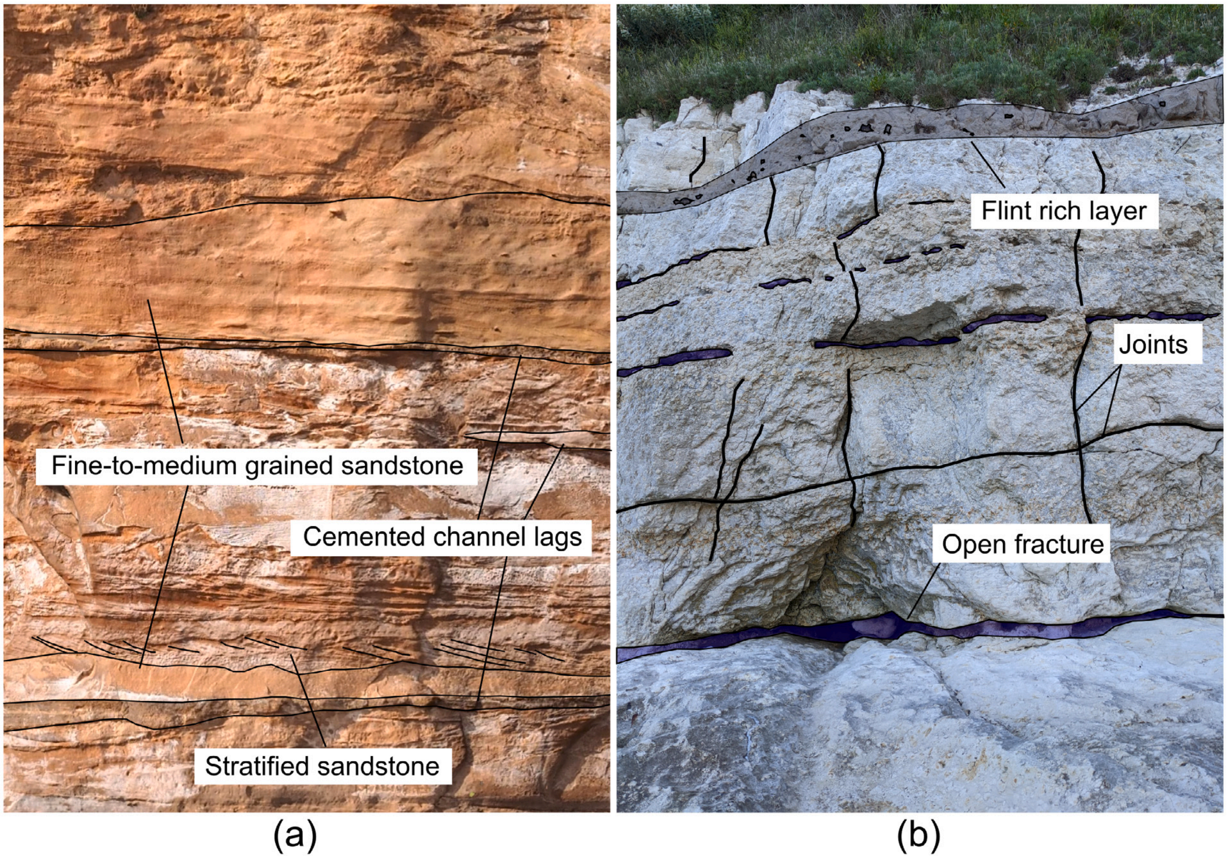

Fig. 17. Examples of geologic heterogeneity in UK principal aquifers observed at outcrop: (a) Sherwood Sandstone group at Ladram Bay, Dorset (UK) (b) Middle Chalk in Beer, Devon (UK).

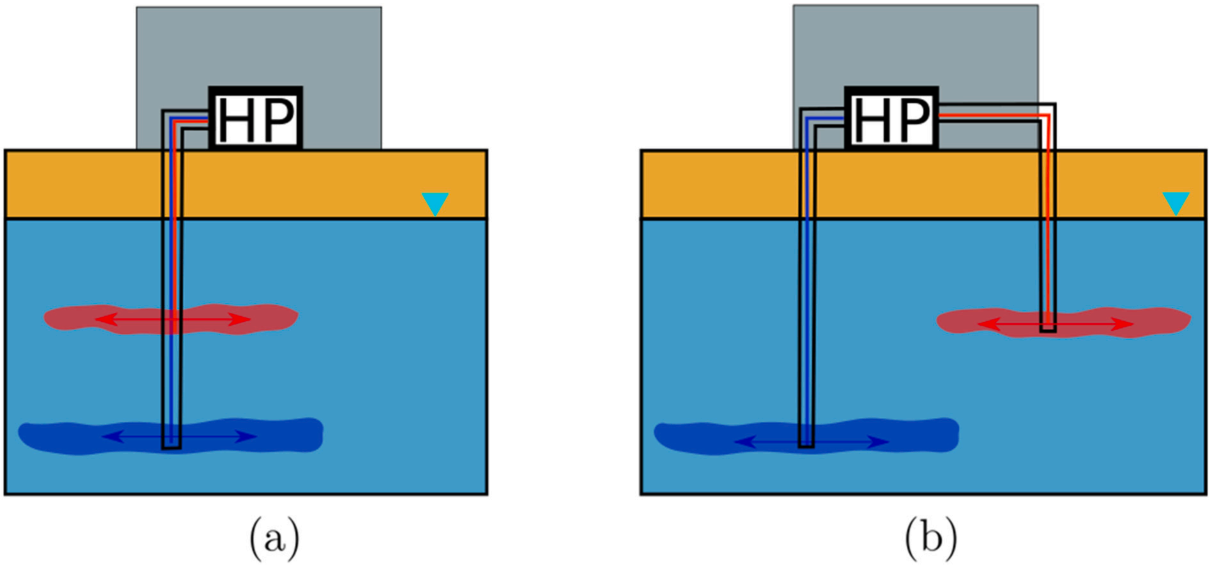

Fig. 18. Thermal plumes in ATES systems are typically offset laterally (Fig. 1f), but vertical offsetting could make more efficient use of aquifer space in thick aquifers with low vertical permeability. Plumes could be stored and produced at different levels via (a) a single borehole with separate warm and cool tubing and screens, or (b) separate warm and cool boreholes with different screen depths.

open-loop, shallow geothermal deployments in the UK are dominated by GWHP and GSHC systems, despite their lower efficiency. There is an important need to inform key stakeholders, such as policymakers, regulators, developers and the public, of the large scale potential of ATES in the UK and communicate successful deployments of ATES both in the UK and abroad. Work is ongoing to deliver this information [80].

8. Discussion

ATES is one of several types of low carbon, shallow geothermal heating and cooling technologies that could be widely deployed in the UK (Fig. 1). In locations or developments where ATES installations cannot meet heating and cooling demand, the technology can be integrated with other low carbon energy sources. For example, the ATES deployment at One New Change in London (Table 4) operates in combination with 219 thermally active piles [81] that exchange heat with the London Clay aquitard that overlies the Chalk aquifer [82]. Although not investigated here, there is broad scope to further increase the proportion of UK heating and cooling demand that is supplied by geothermal: technologies such as BTES and thermally active piles can operate where there is no aquifer, or in aquitards that overlie aquifers; moreover, many UK urban centres have the potential to exploit minewater thermal energy [83] or deep geothermal energy [84]. ATES has been successfully integrated with other renewable energy sources, such as solar photovoltaic [70]. Hybrid ATES systems can be considered when designing heating and cooling systems, to maximise use of the subsurface energy resource and associated as CO_2 emissions savings.

The aquifer requirements, borehole infrastructure and surface facilities required for ATES and GWHC systems are very similar; the main difference is in the mode of operation. As shown here, GWHC systems can provide both heating and cooling with higher efficiency and lower CO_2 emissions than ASHP, but are less efficient than ATES systems so long as the thermal recovery factor of the ATES system is greater than zero. The additional efficiency and lower electrical grid requirements offered by storage and re-use of thermal energy – especially for cooling – suggests that ATES should be considered ahead of GWHC when considering an open-loop geothermal deployment for both heating and cooling. GWHP installations that provide heating or cooling but not both are inherently imbalanced, increasing the risk of thermal interference with an ever growing waste plume which will negatively impact system sustainability. Most developments need heating; when offered, cooling demand is often similar to, or even exceeds, heating demand, which suggests that a balanced ATES system should be considered ahead of a GWHP system when possible.

Given the UK is currently in the emerging phase of ATES development [8], experience from previous projects in the UK and other countries will be key to optimally design ATES systems, effectively manage the subsurface resource and efficiently regulate these systems. In the Netherlands, early ATES installations were permitted on a ‘first come, first served’ basis with no integrated planning of location and operation, resulting in suboptimal use of subsurface space [30]. To avoid ATES systems adversely interfering, current permits in the Netherlands require systems to be separated by $3R_{th}$ [66]. However, ATES systems typically use <50% of the permitted subsurface resource which has led to significant under-utilisation of the subsurface and, particularly in urban areas, a lack of subsurface space for new ATES installations [65]. Methods for efficient planning of ATES to maximise CO_2 emissions savings have been proposed [13,30,67] and could be adopted to regulate the development of new ATES projects in the UK, whilst recognising the additional geologic heterogeneity of UK aquifers and the engineering design changes required to accommodate this.

Experience of ATES deployments elsewhere provides evidence that they are economically as well as environmentally attractive. ATES deployments typically have higher CAPEX than conventional heating, ventilation and air-conditioning (HVAC) systems (typically of order 2–3 times more expensive, depending on market conditions) but significantly lower OPEX (typically of order 5–7 times less expensive, depending on market conditions, particularly energy prices), reflecting lower fuel costs. Payback times for ATES systems installed to date, where data have been reported, range from <2 to ca. 10 years [8, 11,71]. Financial data for UK installations were not available during preparation of this paper. Similar to other place-based, renewable energy sources, ATES systems have the advantage of protecting consumers from fuel price volatility and offer energy security. Unlike wind or solar, and similar to other geothermal and UTES technologies, ATES offers steady heating and cooling supply. However, the higher CAPEX represents a barrier to widespread deployment, especially in emerging markets such as the UK where the nascent state of the technology means costs are typically higher. Policies could be developed to create a supportive political and economic environment, establish building energy efficiency requirements, train and certify local installers, and integrate ATES into national and local energy planning [80].

In this study, we have focused only on low temperature ATES (LT-ATES), where injected water temperature is typically <25 °C. However, current research and previous deployments have also extended to high temperature ATES (HT-ATES) in which water is stored at temperatures >40 °C [8,50,85]. Though there is currently no legal framework in the UK for the development of such systems, they could allow for further decarbonisation of heating. HT-ATES enables heating to be supplied without a heat pump, leading to even higher energy efficiency compared to LT-ATES [86]. A new configuration for ATES based on well triplets has been proposed by [87], which would allow both heating and cooling to be supplied without a heat pump. In this configuration, a cold well is used to store and produce cool water (ca. 5 °C), a hot well is used to store and produce hot water (ca. 40–70 °C), and a buffer well is used to return groundwater which is neither cold nor warm enough to deliver direct cooling or heating (ca. 15–35 °C). With this ATES system design, CO_2 emissions could be further decreased by a factor of 10 compared to conventional LT-ATES [87].

HT-ATES allows for integration with other sources of heat; for example, waste heat from industrial processes or excess energy from renewable sources such as wind and solar [4,71,85,88]. In the UK, [4] estimated the waste heat from industry and solar thermal that could be harvested is approximately 944 TWh or 1.1 times the current heat demand in the country. HT-ATES therefore could be a key technology to further decarbonise heating in the UK at large scale.

9. Conclusions

Aquifer Thermal Energy Storage (ATES) could play a substantial role in decarbonising heating and cooling of the UK’s built environment. The technology is suitable for deployment across the UK, which has a temperate climate with seasonal variations in demand for heating and cooling, widespread availability of suitable aquifers, and a high correspondence between aquifer availability and demand for heating and cooling. ATES has the potential to supply ca. 61% of UK heating and 79% of cooling demand, with reductions in electricity usage and CO_2 emissions of order 13%–41% for heating, and 70%–94% for cooling, compared to conventional open-loop shallow geothermal systems and air-source heat pumps. The higher efficiency of ATES is obtained because waste heat and cool is captured, stored and re-used. ATES offers cooling as an almost free byproduct of heating. Although the UK’s national cooling demand is currently low compared to heating, cooling demand in many new building developments is similar to, or larger than, heating demand; national cooling demand will increase in the near future due to rising summer temperatures.

ATES is a relatively unknown technology in the UK, despite the first UK system having been installed in 2006. Currently, there are just 11 active deployments supplying <0.01% of the UK’s heating and <0.5% of cooling demand. The Wandsworth Riverside Quarter development in London represents a successful ATES deployment in the UK, operating in the Chalk aquifer. However, analysis of data from some other UK systems suggest sub-optimal performance, related to problems such as incorrect system operation after installation, unbalanced provision of heat and cool, and incorrect predictions of groundwater flow in geologically heterogeneous aquifers. The UK can benefit from experience of both successful and unsuccessful deployments, but these need to be more widely reported. The nascent status of ATES in the UK is in marked contrast to international examples, particularly the Netherlands.

A key requirement for sustainable ATES operation is to ensure balanced storage and extraction of heat and cool in the aquifer. Enforcing energy balance requires monitoring of injection and production flowrates and temperatures, along with interpretation of the data to calculate the energy balance ratio. These monitoring data also allow early identification of any problems with system operation. Enforcing energy balance requires ATES systems to be specifically identified in regulatory databases, and regular collection and interpretation of monitoring data. Licensing of new installations should consider the higher efficiency of ATES compared to GWHC systems, efficient use of the available subsurface space, accounting for geological heterogeneity and its impact on thermal plume geometries, and enforcement of energy balance to ensure subsurface temperature changes remain within an identified range. Experience from international examples can inform policy reforms and development of an efficient regulatory framework to facilitate wider adoption. A multifaceted approach to address barriers to deployment is required, involving stakeholders from both public and private sectors. The analyses and findings of this paper are applicable elsewhere in regions with similar climatic and geological conditions, and limited or no uptake of ATES.

CRediT authorship contribution statement

Matthew D. Jackson: Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Geraldine Regnier:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis. **Iain Staffell:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis.

Declaration of competing interest

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

Data availability

The authors do not have permission to share data.

Acknowledgements

Authors Jackson and Staffell grateful acknowledge funding from the UK Engineering and Physical Sciences Research Council (EPSRC) via the ATESHAC project (www.imperial.ac.uk/earth-science/research/research-groups/ateshac/) (grant number EP/V041878/1). Author Regnier grateful acknowledges funding from the EPSRC, United Kingdom via the Centre for Doctoral Training in Fluid Dynamics across Scales. SSE Energy Solutions are thanked for generously sharing data from the Wandsworth Riverside Quarter ATES system. Staff at the UK Department of Energy Security and Net Zero (formerly the Department of Business, Energy and Industrial Strategy) are thanked for helpful comments and feedback on earlier versions of the research and manuscript.

Appendix A. Monte-Carlo simulation of heating and cooling delivered by ATES

A Monte-Carlo simulation was undertaken to assess the heating and cooling that could be delivered locally (per km^2) and nationally by ATES. Data to constrain the input variables when estimating local heating and cooling supply (Eqs. (14) and (15)) are sparse, so we estimate maximum, minimum and mode and assume a linear variation in probability between these values, yielding a triangular probability distribution for each variable [33]. We assume the input variables are independent of each other.

Maximum, minimum and mode for each variable are given in Table 2. Aquifer temperature, groundwater temperature change, thermal recovery and effective screen length are based on data compilations for operating systems, primarily in Europe but including Wandsworth Riverside Quarter (Table 5); [7,8,11,12,21,29,30,54,65,67,71,89]. The minimum screen length is chosen to be small (2 m) to reflect the heterogeneous nature of UK aquifers and its potential impact on plume geometry (e.g. Fig. 8); likewise, the mode screen length is chosen to be closer to the minimum. The maximum screen length is consistent with the typical thickness of aquifer units in the UK, and maximum screen length deployed in operating ATES systems [54]. The heat pump COP for heating is taken from the range observed in Fig. 3A; direct cooling is assumed without use of a heat pump.

The fraction of aquifer in each km^2 available for use is poorly constrained. Typical controls on the value of f include local variations in borehole productivity caused by aquifer heterogeneity [41,48,64], availability of surface space for the installation [7], excess spacing between boreholes in a given ATES system and between neighbouring systems [65]; conflicts with other groundwater uses such as potable water extraction and concerns with groundwater quality [72]; local environmental restrictions relating to groundwater level and quality [90], and conflicts with other uses of the subsurface [7].

Here we assume f varies between zero and 0.4 (Table 2). The minimum value assumes that none of the aquifer is available; the maximum value approximates the Dutch model for well spacing ($3R_{th}$) assuming no other conflicting use of the aquifer. The mode is mid-way between the maximum and minimum, and is based on data from London, where aquifer availability for ATES deployment may be restricted by potable water abstraction, management of minimum groundwater levels and the relatively small number of currently operating shallow geothermal systems (of order 50), including the ATES systems listed in Table 4 [91]. Current use suggests >40% of any given km^2 is available for use (f = 0.2) [91] and we choose this to be the modal value. We assume similar limitations will apply in other UK cities.

Appendix B. Monte-Carlo simulation of electrical demand and CO$_2$ emissions per unit heating/cooling energy supplied by different technologies

We assess the electricity demand and CO$_2$ emissions for different heating and cooling technologies using a Monte-Carlo approach. Data to constrain the variables required to estimate electricity demand and CO$_2$ emissions are sparse, so we again estimate maximum, minimum and mode and assume a triangular probability distribution for each variable, and that the input variables are independent of each other (Table 3). Aquifer temperature, groundwater temperature change and thermal recovery are reported in Table 2. The electrical energy required per unit volume groundwater production is taken from [68] and references therein, and represents the electrical energy required to produce unit volume of groundwater, pass this groundwater through the heat exchanger, and inject it back into the aquifer, along with control systems and ancillary pumps on the building side. The range of values of the coefficients a, b and d and the exponent b in the regression for COP (Fig. 3A) yield a reasonable match to the measured data.

The COP values for ASHP used to calculate electricity consumption and associated CO$_2$ emissions are based on the UK Energy System Catapult field trial of 292 heat pumps in UK homes [92], yielding a mean COP = 2.8 and an inter-quartile range from 2.5 to 3.1. The electricity consumption per kW$_{th}$ heat or cool delivered was calculated using the measured mean and range of COP values and Eq. (11), and the carbon intensity using the data shown in Fig. 3B.

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