Chapter 4

Geothermal Heating and Cooling: Applications for the United Kingdom's Industrial, Municipal, Residential, and Technology Sectors

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Geothermal heating and cooling from shallow systems, minewater networks, and deep aquifers already provide clean, low-cost, reliable energy for UK homes, hospitals, and campuses. But these resources could be used much more widely. Aquifer thermal energy storage alone could meet more than 60% of heating and nearly 80% of cooling demand. Expanding these methods could make geothermal a cornerstone of the UK's heat system.

The United Kingdom already has working, world-class examples of geothermal heating and cooling that are cutting carbon, saving money, and protecting heritage—proving that the technology is ready to scale now. From Bath's Roman springs heating historic landmarks to Southampton's pioneering district network, Gateshead's minewater schemes revitalising coalfield communities, and London's aquifer storage enabling low-carbon heating and cooling, geothermal is delivering reliable, cost-competitive energy across diverse settings. Shallow systems are already cheaper than wind and solar, while deep projects unlock massive long-term capacity, showing geothermal can compete head-to-head with mainstream renewables. The common success

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This chapter has been developed through contributions from a wide range of authors, each responsible for specific sections. **Matthew Jackson** prepared the aquifer thermal energy storage and Wandsworth case study. **David Banks** prepared the section on shallow geothermal. **Helen Doran, Mark Ireland, Jon Gluyas**, and **Gioia Falcone** contributed to the Southampton and Bath case studies. **Helen Doran** performed the analysis and prepared the section on geological cooling and storage for the UK's AI Growth Zones. Editorial responsibilities were coordinated by **Helen Doran**, **Mark Ireland**, and **Jon Gluyas**.

factors—strong governance, public-private partnerships, and integration with complementary heat sources—make these projects not just technically feasible, but economically bankable as well. Geothermal heat is not a future ambition but a proven solution. Collectively, these case studies highlight that geothermal innovation is already embedded in the UK's energy transition. Scaling these models nationwide will slash emissions, tackle fuel poverty, enhance energy security, and turn Britain's geology and industrial legacy into a cornerstone of its transition to renewable and sustainable energy. This chapter outlines immediately deployable, scalable opportunities for heating (and cooling) across the UK.

In terms of heat applications, shallow geothermal technologies offer the lowest levelised costs of heat among geothermal options, primarily due to their maturity, established supply chains, lower construction costs, and strong contractor competition. For heating-only applications, shallow systems typically deliver heat at between £18 and £56 per megawatt-hour[1] (assuming an Nth-of-a-Kind [NOAK] project starts in 2024), with costs falling further when systems are designed to provide both heating and cooling, a particularly advantageous setup in buildings like hospitals. These systems' lower risk profile allows for a reduced hurdle rate (around 7.5% compared with 10.1% for deep geothermal), though higher assumptions would increase costs—for example, a shallow minewater network could rise from £30 per megawatt-hour to £36 per megawatt-hour[2] if the hurdle rate increased to 10%. While shallow systems avoid the high drilling costs associated with deep geothermal, they do require additional investment in heat pumps to raise extracted temperatures to usable levels.

Deep geothermal options for heat (including new deep doublets and repurposed oil and gas wells) are more expensive up front: Doublets range from roughly £84 to £172 per megawatt-hour, while repurposed wells cost between £55 and £100 per megawatt-hour. However, doublets deliver much higher heat output and are widely proven in Europe (see Chapter 3's section titled "Modelling Future Production Scenarios for the Wessex Basin"). Costs for deep systems reflect project risk. For instance, a higher hurdle rate during the drilling phase can push a deep doublet from about £126 to £264 per megawatt-hour, whereas reducing risks can improve cost-effectiveness.

SHALLOW GEOTHERMAL SYSTEMS

There is no formal definition of "shallow" geothermal in the United Kingdom, but a working definition might include systems shallower than 300 metres (also the upper defined limit for "deep level land" in the Infrastructure Act 2015):[3]

- **Thermal extraction systems**, which transfer heat or cooling from the subsurface but do not store energy (**Figure 4.1a, b**).
- **Underground thermal energy storage systems**, in which heat or cooling is stored for later use (**Figure 4.1c–e**).

Both categories can be configured as either closed-loop or open-loop systems. In closed-loop systems (**Figure 4.1a, d)**, a heat transfer fluid circulates within sealed pipes or boreholes, exchanging heat with the surrounding soil or rock. In open-loop systems (**Figure 4.1b, c, and e**), groundwater is pumped from and returned to the subsurface via one or more boreholes, enabling direct extraction or storage of thermal energy.

Heating and cooling systems that use the ground to supply energy to a heat pump are often called ground source heat pump (GSHP) or ground source heating and cooling (GSHC) systems. Open-loop systems are sometimes referred to as groundwater heat pump (GWHP) or groundwater heating and cooling (GWHC) systems. In this report, GWHP is used to refer to systems that supply heating or cooling only, and GWHC is used when they provide both.

There are several main approaches to extracting heat from the shallow subsurface:

1. A groundwater-based "**open-loop**" GSHC system: If a permeable aquifer horizon is present in the shallow subsurface, a water well can be drilled. Groundwater can be pumped from the well and passed through a heat pump system, which extracts heat from the water. Note that the "thermally spent" water must be disposed of responsibly. To conserve water resources, environmental authorities will normally insist that this water is returned to the aquifer via a reinjection well (see "Underground Thermal Energy Storage in the UK, with a Focus on Aquifer Thermal Energy Storage"). A special class of

GROUND SOURCE AND UNDERGROUND THERMAL ENERGY STORAGE SYSTEMS

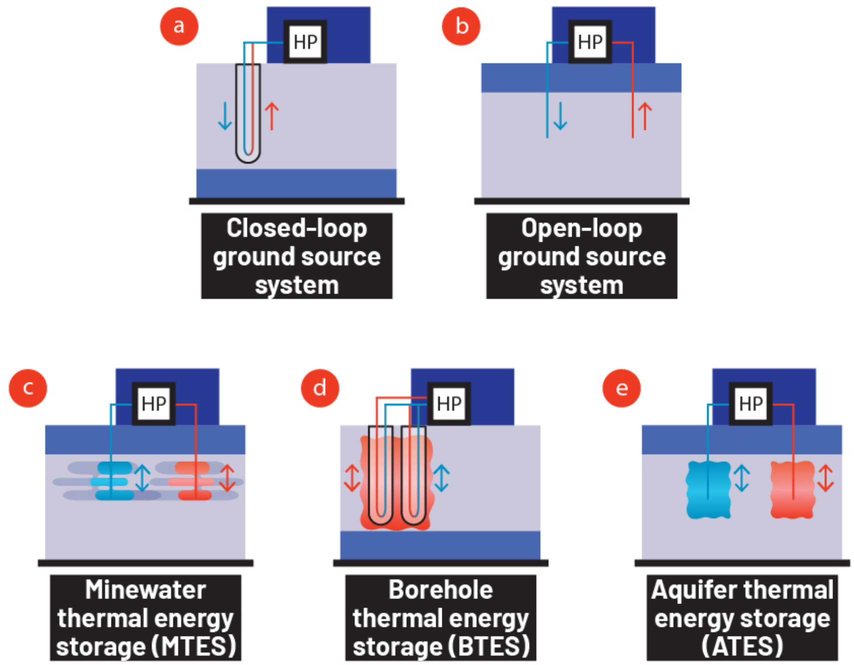


Figure 4.1: Schematics illustrating (a, b) ground source and (c, d, e) underground thermal energy storage systems for low-carbon heating and/or cooling. Source: Modified from Jackson, M. D., Regnier, G., & Staffell, I. (2024). Aquifer thermal energy storage for low carbon heating and cooling in the United Kingdom: Current status and future prospects. *Applied Energy, 376*, 124096.

open-loop system is one in which water is pumped from flooded, abandoned mines for the purpose of heating or cooling (see "Minewater Geothermal Energy in the UK").

2. A shallow, **horizontal closed-loop** system: In this system, one or more loops of polyethylene pipe are buried between 1.2 metres and 2 metres deep in soil trenches. A heat transfer fluid (a solution of glycol or alcohol) circulates through the pipes, collecting heat from the soil and returning it to a heat pump, where heat is extracted before the fluid is recirculated. This may not sound like "geothermal," and indeed, much of the heat from such systems is derived from solar energy being absorbed by the soil. But the heat is stored in the ground and, as such, represents the "shallowest" end of the geothermal spectrum.
3. A **vertical closed-loop** system or borehole heat exchanger (BHE): In this system, a borehole is drilled (often to between 60 metres and 250 metres deep) and a loop (U-tube) of polyethylene pipe is installed. Heat transfer fluid is circulated around the loop, absorbing heat from the rocks in the borehole wall and delivering it back to the heat pump. Around 250 metres deep and below, U-tubes become hydraulically inefficient and coaxial circulation systems can be used in deeper borehole heat exchangers.[4]

While most shallow geothermal systems are designed for heating, they are inherently reversible and can be operated to reject waste heat and provide cooling. In some geological settings, it is also possible to store surplus heat generated in summer for recovery during the winter (see "Underground Thermal Energy Storage in the UK, with a Focus on Aquifer Thermal Energy Storage").

Ground Source Heat Pumps

The shallow GSHP sector is the one area of geothermal that has, to date, enjoyed significant uptake in the UK. It also has a historic pedigree: The world's first GSHP was used to freeze ground during shaft excavation in Swansea in 1862;[5] probably the world's first groundwater-sourced domestic heat pump was installed in Perthshire, Scotland, in the mid-1920s.[6,7] Much of the pioneering experimental work on ground heat exchangers was carried out by Miriam Griffith and John Sumner in the United Kingdom from the 1950s through the 1970s.[8,9,10] The UK has a particularly active Ground Source Heat Pump Association (GSHPA)[11] that produces standards for the construction of GSHP systems.[12]

THERMODYNAMICS OF GEOTHERMAL HEAT ENGINES, HEAT PUMPS, AND DIRECT-USE SYSTEMS

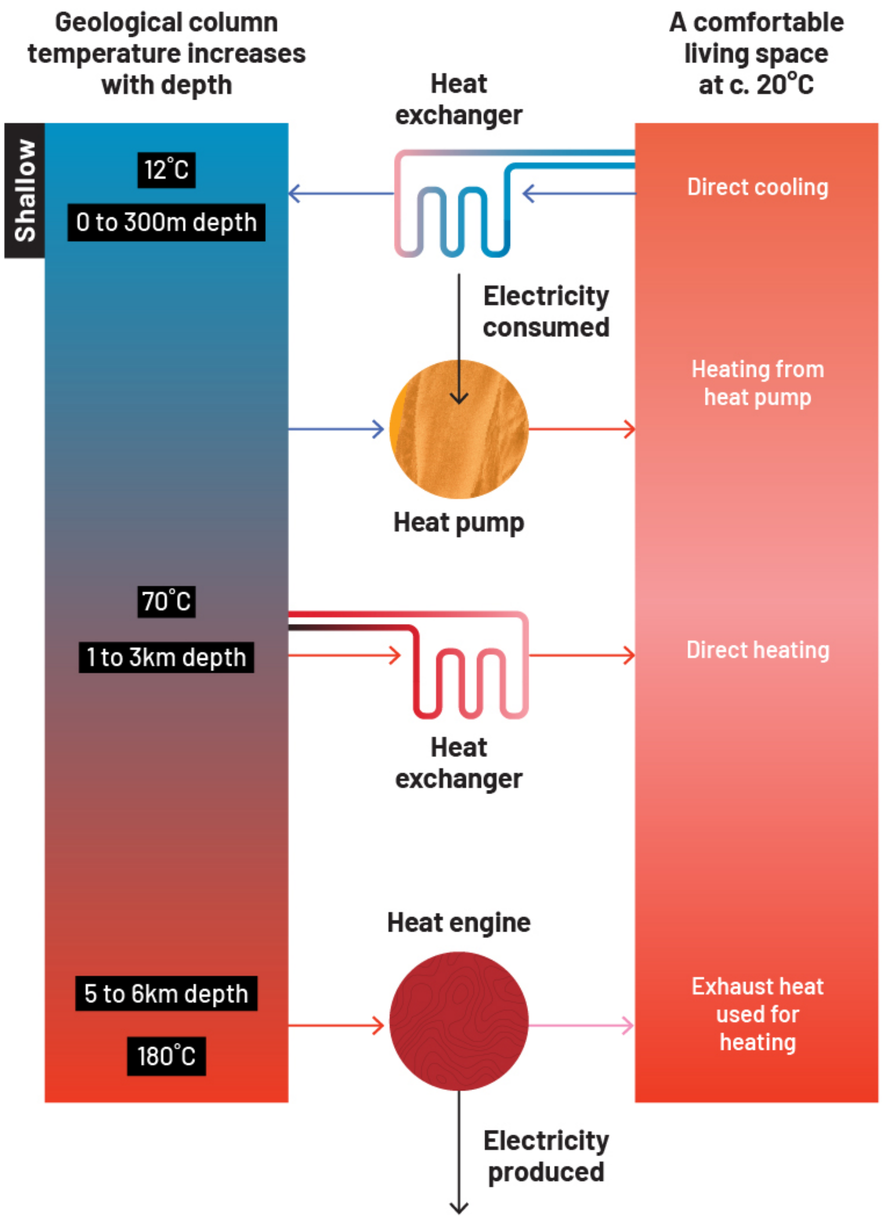


Figure 4.2: The simplified thermodynamics of geothermal heat engines, heat pumps, and direct-use systems. Source: David Banks.

The Heat Pump

In deep geothermal boreholes drilled in rocks with a high geothermal gradient (such as United Downs in Cornwall), it may be possible to extract hot fluids at temperatures high enough to generate electricity. In thermodynamic terms, the high-temperature heat flows through a heat engine to a lower-temperature exhaust. In the engine, heat is converted to mechanical work (turbine) and then to electricity (**Figure 4.2**).

In medium-depth geothermal prospects (such as the deep Triassic, Sherwood Sandstone), it is possible to extract fluids that are not hot enough for viable electricity generation but that can provide heat, via direct heat exchange, to a consumer such as a district heat network, large user (for instance, warehouse or hospital), or agricultural enterprise.

At shallow depths, temperatures in the UK are seldom warm enough for such direct use. To be able to extract heat from cool ground, the thermodynamic opposite of a heat engine is required—that is, a heat pump. A heat pump uses electricity to perform mechanical work (a compressor) to transfer heat from a low-temperature source (the ground) to a high-temperature sink (a heating system). Provided the electricity used is low carbon and relatively cheap, shallow geothermal prospects are attractive because the capital costs, risks, and uncertainties of deep drilling are avoided. A shallow geothermal system that uses a heat pump is often called a GSHP system. The efficiency of such systems is described in terms of coefficient of performance (COP), or the ratio of heating output to the electrical energy consumed. A COP of 2 for a heat pump means that it produces twice as much heat as the amount of electrical energy it consumes, but heat pumps are typically designed to be more efficient than this, so one will often aim for a COP of at least 3 for a GSHP.[13,14]

Although shallow groundwater and rocks usually require a heat pump to provide heating to a customer, they are cool enough to provide direct cooling.

Where Can Shallow GSHPs Be Developed?

Shallow GSHPs can be developed almost anywhere in the United Kingdom, subject to meeting the licensing and permitting requirements of the relevant regulatory authority (see, for example, the Environment Agency's guidance on permitting closed-loop[15] and open-loop[16] systems in England). Open-loop groundwater-based GSHC systems require an aquifer that will yield the required quantity of water. Horizontal closed-loop GSHPs can be developed where there is sufficient land area that can be excavated to at least 1.2 metres deep and is likely to remain undisturbed for the foreseeable future.

Vertical borehole GSHC systems can be developed in almost any ground condition and underlying rock type. The more quartz-rich and compact the rock is, the better the thermal conductivity of the ground (quartzites, sandstones, and granites are particularly attractive). Dry porous rocks or sediments will have low thermal conductivity. Environments that can be problematic for BHE construction include locations underlain by shallow mine workings or caves, areas with artesian groundwater head (pressure that causes groundwater to rise above the top of the aquifer or surface), lithologies where soluble evaporite minerals (for example, salt and anhydrite) are present, or lithologies where there is risk of petroleum or gas presence. The British Geological Survey (BGS) has a screening tool for evaluating the suitability of geology for both open- and closed-loop solutions.[17,18]

Shallow Geothermal Systems in the UK

By 2021, according to an estimate reported by the Environment Agency, around 43,700 GSHP units had been sold for installation in the UK, probably representing between 30,000 and 38,000 GSHC systems (a system may use more than one heat pump).[19] The vast majority of these are closed-loop, modestly sized domestic systems.

Since the introduction of the government's Boiler Upgrade Scheme subsidy in 2022, however, sales of domestic GSHP systems for retrofit have declined significantly because the current subsidy of £7,500 typically covers more than half the cost of an air source heat pump installation but only a small fraction of the cost of a GSHP system, disincentivising prospective GSHP investors.

The long-awaited introduction of the Future Homes Standard is anticipated to force all new homes to be equipped with non-fossil-fuel heating.[20] This requirement should provide a boost to the domestic GSHP sector, given the former and current government's intentions to build 300,000 new dwellings per year.[21] The standard will also drive continuing improvements in the efficient thermal construction of homes, allowing them to be effectively heated by low-temperature hydronic emitter systems (which are well suited to heat pumps), rather than the high-temperature radiator systems installed in poorly insulated houses during the "coal age" and "gas age."

Rebalancing environmental and social levies on electricity towards gas would narrow the "spark gap" between electricity and gas prices and would therefore also incentivise operation of heat pumps.[22]

The commercial, industrial, and public GSHC sector is more buoyant than the domestic sector, with between 500 and 1,000 smaller (<100 kilowatts) and between 60 and 80 larger (>100 kilowatts) non-domestic GSHC systems installed per year in the United Kingdom as of 2023.[23]

Almost all groundwater-sourced open-loop GSHC systems require an abstraction licence from the regulatory agency (the Environment Agency [EA] in England). As of 2023, the number of such systems was still relatively low. There were 149 EA groundwater abstraction licences listing "heat pump" as a usage (median heat transfer capacity estimated as around 208 kilowatts) in England and 174 groundwater licences listing "low-loss" or non-evaporative cooling as a use (of which three also listed "heat pump").[24]

Distribution

Most (but not all) modestly sized, retrofitted GSHP systems in the UK will be registered with the Microgeneration Certification Scheme (MCS), which has a database of installations. The largest densities (relative to number of households) of MCS-accredited GSHP installations in the UK (of which the majority are domestic, retrofit, closed-loop installations) are in Cornwall, northern Scotland, central Wales, and Shropshire. The uptake of GSHPs has generally been low in the main urban areas (**Figure 4.3**).

The highest numbers of EA groundwater-sourced open-loop heat pump abstraction licences are located in the Thames region. Those for "low-loss" or non-evaporative cooling are in the northeast, northwest, and Midlands of England and are used in the metals, machinery, electronics, chemicals, and food and drink industries.[25]

Networking Shallow Geothermal

Shallow geothermal lends itself to incorporation within fourth- and fifth-generation district heating and cooling networks (DHCNs). In fourth-generation systems, an array of GSHPs are typically installed in an energy centre and coupled to an open-loop well doublet or vertical or horizontal subsurface heat exchangers.[26] The heat pumps in the energy centre then distribute low-temperature waterborne heat (often at between 50°C and 60°C) around a district heating network. The client properties extract heat from the network via heat interface units (effectively heat exchangers). All variants of shallow geothermal can be connected to such networks.

Several versions of this currently exist, though some have struggled with operational costs. At North Aston Farm Estates, near Bicester, Oxfordshire, a GSHP network was installed to serve 27 properties in a village. The energy centre is supported by an array of horizontal

DISTRIBUTION OF GSHP INSTALLATIONS IN THE UK, BY LOCAL AUTHORITY AREA

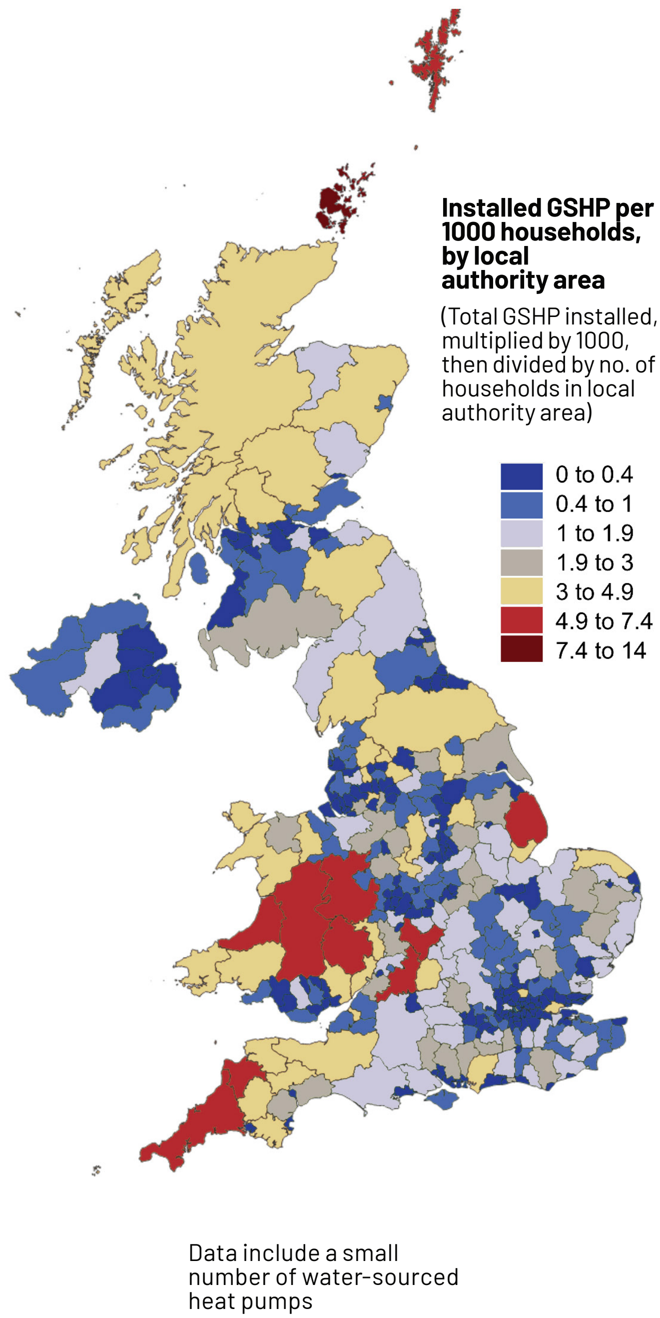


Figure 4.3: Distribution of MCS-accredited ground source heat pump installations in the UK as of July 2025, by local authority area. A total of 33,256 systems had been installed under the MCS scheme as of that date. GSHP = ground source heat pump. Source: Microgeneration Certification Scheme (MCS). (n.d.). *MCS data dashboard*.

ground loops installed beneath a large field. The system reportedly functions well, although the electricity costs associated with heat and circulation pumps have proved challenging, leading to a recent application to construct a solar photovoltaics farm to support the system.[27] A closed-loop BHE-based GSHP network—comprising 28 boreholes to 100 metres deep and three 40 kilowatt heat pumps—was installed in 2012 to serve 18 flats at Hartshorne, South Derbyshire, with a flow temperature of 55°C, although identification of a financial model to cover operational costs has proved challenging.[28,29] Finally, at Wandsworth Riverside (see "Use Cases and Deployment Examples" and the case study in this chapter) in London, more than 1 megawatt of heating and cooling capacity was installed in 2013 to support a network supplying 504 apartments and commercial and leisure space, based on an open-loop system abstracting and reinjecting chalk groundwater from eight 120 metre deep drilled wells.[30]

A fifth-generation DHCN overcomes some of the potential disadvantages of fourth (and earlier) generations.[31] They have no centralised energy centre. Instead, a network of heat transfer fluid is directly coupled to the ground, such as via a number of BHEs, which can be in a central array or distributed around the network (**Figure 4.4**). The heat transfer fluid circulates throughout the network at near-ambient temperature (5°C–30°C), and the pipes thus require no insulation. Client properties have their own heat pumps, extracting heat from—or rejecting surplus heat to—the ambient loop and delivering heating or cooling at a temperature determined by the client.

One advantage of these ambient networks is they are typically largely self-regulating, meaning the management, maintenance, and financial models for fifth-generation DHCNs are far simpler than for fourth-generation ones, as clients own heat pumps and are responsible for the electricity required to run them. Communal or utility

FIFTH-GENERATION DISTRICT HEATING AND COOLING NETWORK

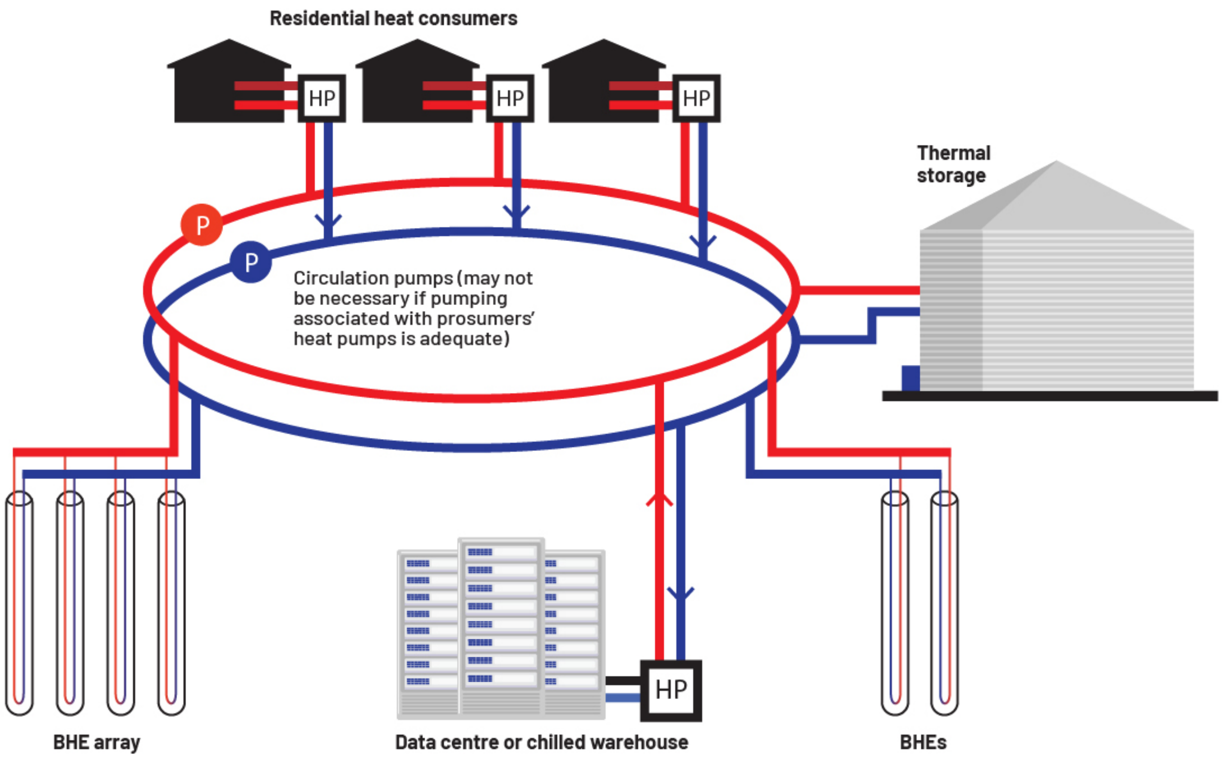


Figure 4.4: Schematic diagram of a fifth-generation district heating and cooling network, coupled to shallow geothermal BHEs, heating and cooling clients, and thermal storage. BHE = borehole heat exchanger; HP = heat pump. Source: David Banks, personal communications, 2025.

responsibility is thus restricted to the ambient loop and geological collectors themselves and could be financed via a simple standing change. There are early examples of large fifth-generation DHCNs globally, such as the minewater-coupled network in Heerlen, the Netherlands.[32] The concept is relatively new to the UK, but the company Kensa has pioneered a BHE-based ambient loop approach in their Heating the Streets project at Stithians, Cornwall.[33] This couples 96 dwellings (each with their own small heat pump), via an ambient loop, to 102 closed-loop BHEs (11,319 drilled metres) in the Carnmenellis Granite.

Along with residential applications, shallow geothermal is also well suited to campus-type building clusters (such as at universities and hospitals). At Cheltenham and Gloucester College, two campuses are each supported by around 400 kilowatts of heat pump capacity and a ground array of 40 boreholes to an average of 200 metres deep.[34]

Heat Pump Case Study: Roman Baths Hot Spring Water Heat Recovery System, Bath

Bath sits atop the UK's only truly hot springs, used for more than two millennia and still rising at approximately 45°C to 46 °C beneath the Roman Baths.[35] Today, the city is harnessing this resource through non-contact heat recovery to decarbonise landmark buildings while safeguarding archaeology and water quality (**Figure 4.5**). The programme centres on two complementary schemes: (i) Roman Baths and Pump Room heat recovery, and (ii) the Bath Abbey Footprint project, which captures heat from the adjacent Great Roman Drain.

Roman Baths and Pump Room Heat Recovery

The Roman Baths and Pump Room project captures low-grade heat from the King's Bath via 16 stainless-steel energy exchange blades installed within the spring

BATH ABBEY, UNITED KINGDOM

Figure 4.5: Bath Abbey stands above the Great Roman Drain, where a modern, non-invasive heat recovery system captures geothermal heat from spring water flowing beneath York Street to provide low-carbon heating for the Abbey. Adjacent, the Roman Baths demonstrate nearly two millennia of continuous geothermal use, with the Great Bath still fed by warm, mineral-rich waters rising from deep geological formations below Bath.

chamber. A new plant room beneath Stall Street integrates pumps, heat exchangers, and controls, transferring recovered energy into the heating circuits of the Roman Baths, the Pump Room, and the Clore Learning Centre.[36]

This closed-loop system avoids direct contact with the spring water, preserving both water quality and archaeological integrity. With an estimated thermal capacity of approximately 100 kilowatts, the installation supplies up to two-thirds of annual heating demand for the served buildings, with output temperatures reaching around 75°C for the Roman Baths and approximately 55°C for the Clore Learning Centre. [37]

Bath Abbey Footprint Project

As part of the £19.3 million Footprint project, Bath Abbey has installed a complementary heat recovery system within the Great Roman Drain, located beneath York Street. Here, 10 custom-built EnergyBlade® heat exchangers extract heat from spring water flowing towards the River Avon.[38] The recovered energy feeds two Ecoforest heat pumps (ecoGEO HP 25–100 kW units), which upgrade the temperature to supply year-round underfloor heating throughout the Abbey and associated facilities.[39]

To ensure heritage protection, the system operates entirely non-invasively: The spring water remains isolated from the heating circuits, preventing biological or chemical impacts while maintaining the Abbey's historical character.

Performance, Carbon Savings, and Resilience

Together, these schemes provide reliable baseload heating to some of Bath's most significant heritage sites. The Roman Baths system supplies up to two-thirds of annual heating demand for its connected buildings, while the Abbey's Footprint project enables year-round underfloor heating powered almost entirely by renewable energy.[40,41]

By replacing gas-fired heating, the combined projects significantly reduce operational carbon emissions and contribute directly to Bath & North East Somerset Council's climate goals. System resilience is supported through hybrid integration with existing boilers for peak load; redundancy in plantroom design; and continuous monitoring of flow rates, temperatures, and hydraulic performance.

Lessons for Policymakers and Investors

For policymakers and investors, the Bath schemes highlight the potential of geothermal heat recovery in sensitive heritage contexts. They demonstrate that such systems can be successfully deployed within a United Nations Educational, Scientific, and Cultural (UNESCO) World Heritage setting without compromising cultural assets.[42] The use of non-contact engineering ensures that the spring water remains isolated from the heating circuits, avoiding contamination and protecting fragile archaeological environments.[43] The projects also showcase modular scalability, with multiple small-scale systems acting as anchor loads that could be integrated into larger district heating frameworks in the future. By displacing fossil-fuel-based heating, the schemes directly support Bath & North East Somerset Council's renewable energy ambitions, aligning closely with regional and national climate policy goals.

UNDERGROUND THERMAL ENERGY STORAGE IN THE UK, WITH A FOCUS ON AQUIFER THERMAL ENERGY STORAGE

Concept and Mechanism

Underground thermal energy storage (UTES) involves the capture, storage, and reuse of heat in the subsurface. Waste heat captured from buildings, industrial processes, or excess renewable energy generation in the summer can be stored and used for heating in the winter.[44] Conversely, waste cool can be captured and stored to provide cooling in the summer. Thermal energy is transported from the subsurface using boreholes and a carrier fluid and from the carrier fluid to a working fluid on the building side via a heat exchanger. The temperature of the working fluid can be increased or decreased as required using a heat pump (see "Ground Source Heat Pumps").

Aquifer thermal energy storage (ATES) is a type of open-loop UTES that stores warmed or cooled groundwater in naturally porous, permeable underground rocks and uses this groundwater to provide low-carbon heating and cooling (**Figure 4.1e**). In this chapter, we primarily consider low-temperature ATES (LT-ATES) systems in which storage temperatures are typically between around 15°C and 20°C at the warm wells and between 5°C and 10°C at the cold wells, both because these systems dominate worldwide[45,46] and because a number of LT-ATES systems currently operate in the UK.[47] Other UTES technologies include mine thermal energy storage, in which warmed or cooled water is stored in abandoned mineworkings (**Figure 4.1c**), and borehole thermal energy storage, which can be used when no suitable aquifer or other storage reservoir is available (**Figure 4.1d**).

ATES systems employ pairs of bi-directional wells (termed *doublets*) that inject or produce groundwater depending on the demand for heating or cooling. The wells are defined by the temperature of the groundwater that is stored and produced, so they are called 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 (see **Figure 4.1c**) because ATES systems are distinct in using a natural subsurface aquifer for energy storage. Other open-loop UTES technologies store thermal energy in manmade reservoirs such as abandoned mines, natural caverns, or specially constructed tanks or pits.[48]

The basic operation of a seasonal ATES system is shown in **Figure 4.6**. In winter, warm groundwater is pumped from one or more warm wells. 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) for which the system provides 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 wells.

In summer, the process is reversed: Cool groundwater is pumped from the cold wells, and the working fluid is cooled by the groundwater via the heat exchanger to deliver cooling.[49] In many installations, cooling can be delivered directly without a heat pump.[50] This is direct cooling. In some systems, a heat pump is used to further cool the working fluid. The warmed working

SEASONAL OPERATION OF LT-ATES IN SUMMER AND WINTER

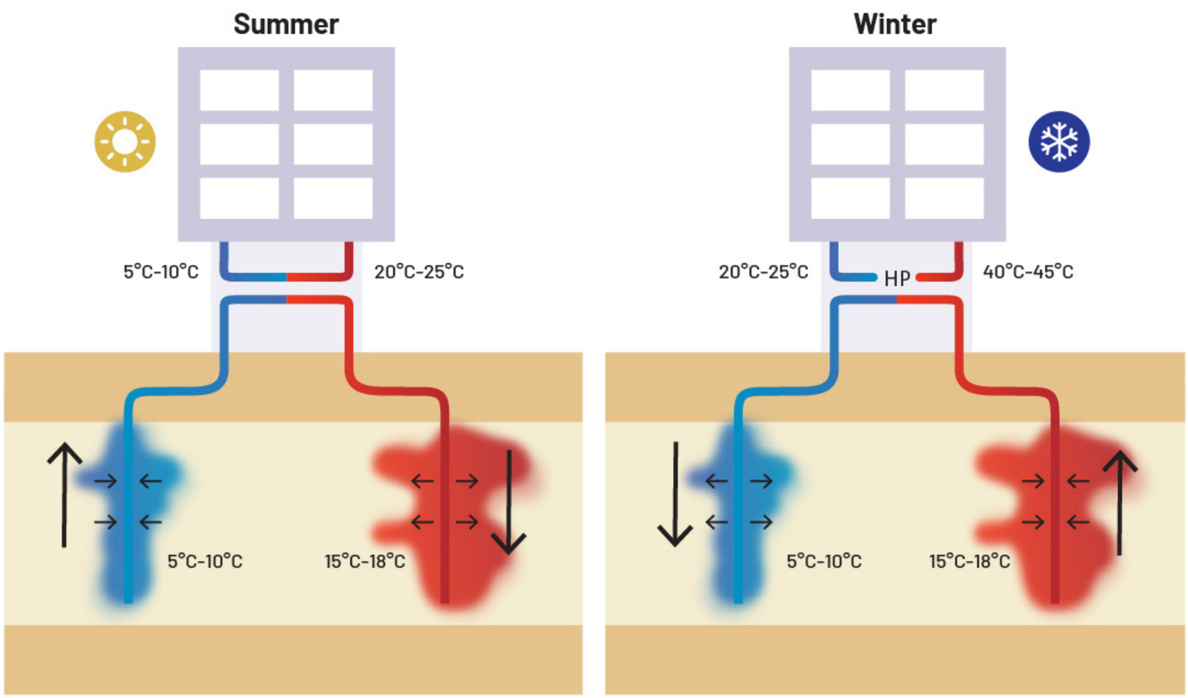


Figure 4.6: Seasonal operation of LT-ATES in summer (left) and winter (right). HP = heat pump. Source: Jackson, M. D., Regnier, G., & Staffell, I. (2024). Aquifer thermal energy storage for low carbon heating and cooling in the United Kingdom: Current status and future prospects. *Applied Energy, 376*, 124096.

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. Only a single doublet comprising a warm well and a cool well is shown in **Figure 4.6**. In practice, the number of doublets can be increased to deliver higher heating and cooling power and storage capacity.

Targets and Initiatives

The basic requirements for deployment of LT-ATES 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 around 300 metres below ground surface) beneath the building(s) supplied by the system. The temperate UK climate is well suited to ATES.[51]

Previous work has assessed UK aquifer suitability and availability for GWHP deployments.[52] The screening tool developed by BGS is available to classify the subsurface as more or less suitable for such open-loop systems with capacities greater than 100 kilowatts thermal but was not specifically developed for ATES. The tool considers aquifer productivity and depth, groundwater chemistry, and protected areas,[53] but only aquifers shallower than 300 metres below ground level are considered. (The tool was initially developed for England and Wales[54] and then further extended to Northern Ireland,[55] 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. No tool is yet available to assess aquifer suitability for ATES or GWHP systems in Scotland, but a thorough overview of Scotland's aquifers has been published by BGS.[56]

Jackson and colleagues noted the spatial correlation between UK heating and cooling demand and the location of suitable aquifers for LT-ATES.[57] They used a probabilistic approach to determine that widespread deployment of LT-ATES could supply roughly 61% of the UK's current heating demand and 79% of cooling demand. To realise this target, 85,000 "typical" ATES systems with a capacity of approximately 3 megawatts thermal would have to be installed. This is a large number, but it should be measured against the 23 million domestic gas boilers still operating. The proportion of demand that could be met using shallow geothermal is likely higher, given that borehole thermal energy storage and mine thermal energy storage could be deployed where there are no suitable aquifers or in addition to ATES systems. Hybrid installations can further maximise subsurface use. One example is the One New Change development in London, which uses energy piles to exchange heat with the London Clay aquitard and an ATES system to store heat in the underlying Chalk aquifer.[58]

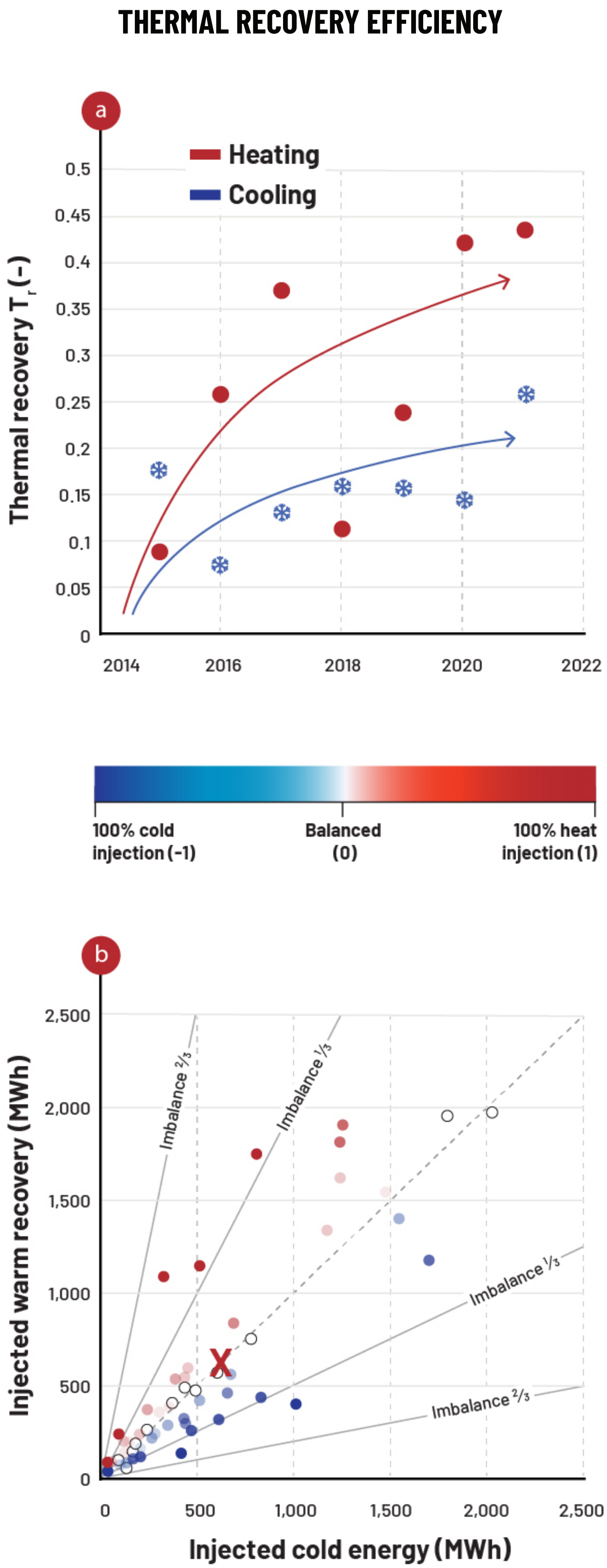
System Performance and Output

ATES systems are characterised by large storage (of order hundred to thousands of megawatt-hours thermal) and power (of order megawatts thermal to tens of megawatts thermal) capacities and can be used to supply large buildings or complexes of buildings or district heating and cooling networks.[59,60] Typical system parameters are summarised in **Table 4.1**. Storage capacity is large compared with that of manmade reservoirs (including thermochemical reservoirs) because of the 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 between 2 watts and 4 watts per metre-kelvin; **Table 4.1**). Power capacity is large because pumping groundwater into and out of the storage reservoir allows rapid transport of energy via advection, especially compared with closed-loop systems that rely

TYPICAL PROPERTIES OF ATES SYSTEMS

Property	Values
Aquifer depth (m)	10s–100s m
Well number	2–10s
Total production/injection rates ($m^3 h^{-1}$)	10s–1000s
Heating/cooling power (MW to 10s MW)	1–10s
Energy storage capacity (GWhth)	1–100s

Table 4.1: Typical properties of aquifer thermal energy storage (ATES) systems. GWhth = gigawatt hour thermal; $m^3 h^{-1}$ = cubic metres per hour; MW = megawatts. Source: Compiled from Fleuchaus, P., Godschalk, B., Stober, I., & Blum, P. (2018). Worldwide application of aquifer thermal energy storage–a review. *Renewable and Sustainable Energy Reviews*, *94*, 861–76.



on conductive heat transport for heat exchange in the subsurface. The storage and power capacity of ATES systems can be increased by adding more doublets, but they are ultimately constrained by two factors: (i) the maximum sustainable well flow rate, and (ii) the temperature of the produced groundwater. As discussed later in this chapter, both must be estimated using numerical simulation models.

An important design consideration for ATES systems is energy balance—that is, the storage and extraction of equal amounts of heat and cool.[61] Energy balance is important for several reasons. First, it ensures sustainability: A balanced system extracts no net heat or cool from the aquifer, so it never exhausts a finite resource. Second, it ensures there is no net change in aquifer temperature. Although temperature locally changes around the warm and cool wells, the net change is zero because there is no net extraction of heat or cool. In the Netherlands, balanced operation is a regulatory requirement. Balance is typically ensured by, where necessary, providing additional sources of low-carbon heating or cooling (**Table 4.2**).[62]

Another important design consideration for ATES is thermal recovery efficiency, which measures the fraction of stored heat or cool recovered to the surface.[63] Thermal recovery efficiencies of greater than 80% are observed in some operating systems.[64] Recovery efficiency is typically lower when there is (i) significant groundwater flow, which tends to move the thermal plumes away from the wells, so the stored heat or cool cannot be recovered unless the system is specially designed;[65,66] or (ii) significant thermal interference, which occurs when

Figure 4.7: (a) Thermal recovery efficiency from the Riverside Quarter low-temperature aquifer thermal energy storage (LT-ATES) system in Wandsworth, London. (b) Energy balance in Dutch LT-ATES systems. Plot shows injected warm energy plotted against injected cool energy. Systems that plot on the dashed line with gradient = 1 are energy balanced. Also shown for comparison is the energy balance of the Riverside Quarter system denoted by the red cross. MWh = megawatt-hours. Sources: (a) modified from Jackson, M. D., Regnier, G., & Staffell, I. (2024). Aquifer thermal energy storage for low carbon heating and cooling in the United Kingdom: Current status and future prospects. *Applied Energy, 376*, 124096; (b) modified from Fleuchaus, P., Schüppler, S., Godschalk, B., Bakema, G., & Blum, P. (2020). Performance analysis of aquifer thermal energy storage (ATES). *Renewable Energy, 146*, 1536–1548.

TEMPERATURE FIELD OF AN ATES SYSTEM

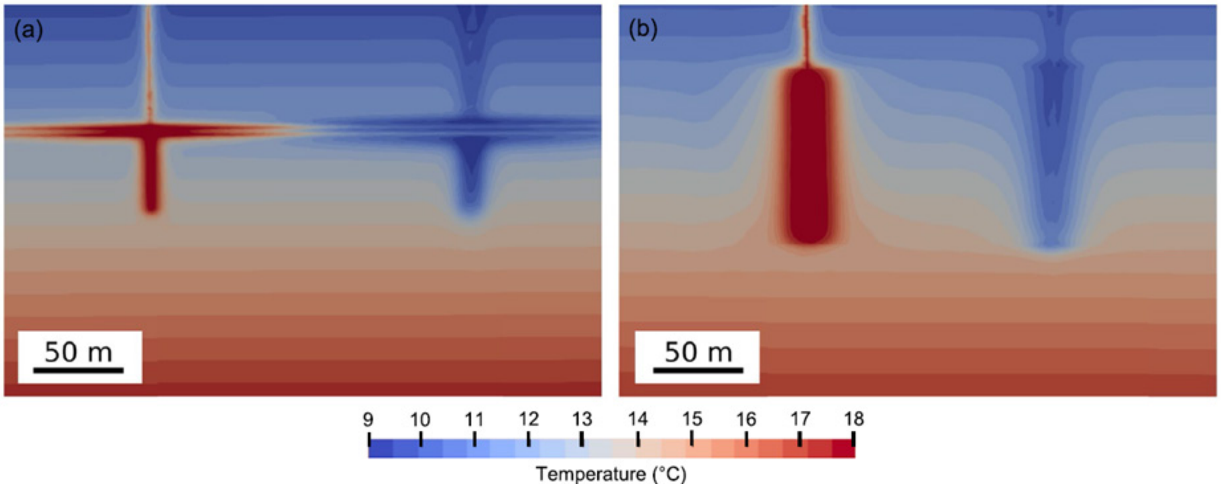


Figure 4.8: Snapshot of the temperature field in a 2D section through a 3D numerical simulation of ATES system operation using a well doublet in (a) the heterogeneous Chalk aquifer in London, and (b) a homogeneous aquifer. Source: Jackson, M. D., Regnier, G., & Staffell, I. (2024). Aquifer thermal energy storage for low carbon heating and cooling in the United Kingdom: Current status and future prospects. *Applied Energy, 376*, 124096.

the warm and cool plumes interact in the aquifer.[67,68,69] Interference typically occurs when warm and cool wells are not spaced sufficiently far apart or the lateral plume spread is larger than predicted due to the presence of geological heterogeneity. For example, in the Chalk aquifer in London, significant lateral plume spread is predicted in high-permeability karst intervals (**Figure 4.8**). If the warm plume reaches the cool wells, and vice versa, then thermal breakthrough occurs, impacting the production temperature and significantly reducing system efficiency.

Jackson and colleagues[70] developed earlier work by Stemmle et al.[71] to demonstrate that the thermal recovery efficiency of a balanced ATES system, with no thermal breakthrough, measures the additional energy supplied by an ATES system as compared with an equivalent GWHC system that sources groundwater at ambient temperature. Thus, a thermal recovery efficiency of zero does not mean the ATES system delivers no low-carbon heating or cooling. Rather, it means the ATES system delivers the same heating and/or cooling energy as an open-loop system without storage.

Jackson and colleagues further showed that ATES systems with thermal recovery greater than zero offer lower electricity consumption and associated CO_2 emissions than equivalent GWHC systems.[72] The reason is simple: Heating is more efficient because ATES supplies pre-warmed groundwater to the heat exchanger, so the heat pump needs to boost the temperature less and operate with a higher COP. Cooling is more efficient because ATES delivers pre-cooled groundwater with a temperature low enough to deliver cooling without a heat pump. Using a probabilistic approach, Jackson et al. estimated that compared with an equivalent GWHC system, ATES offers a reduction in electricity consumption of between 7% and 23% and CO_2 emissions with a mode of 9% for heating (the mode represents the most commonly sampled value in the distribution) and a reduction of between 19% and 93% with a mode of 40% for cooling.[73] The very high efficiency of ATES for cooling is well known;[74,75,76] cooling in an ATES system with high thermal recovery can be thought of as a close-to-free byproduct of heating.

Use Cases and Deployment Examples

ATES was initially deployed in the 1960s in Shanghai, China, to provide cooling to factories.[77] Systems were then installed in other countries, including Switzerland, the United States, France, and Sweden, but the Netherlands remains the leader in LT-ATES systems by far after rapid expansion in the 2000s. Today, of the approximately 3,500 LT-ATES systems worldwide, roughly 3,000 are located in the Netherlands.[78] The Netherlands also hosts the world's

CHARACTERISTICS OF ATES INSTALLATIONS

City (Country)	Purpose	Facility	Year	Well depth (m)	Well #	Maximum flow rate (m^3/h)	Capacity (MW)	Capital costs (Mio. €)	Payback time (years)	CO_2 savings (t/a)
Amersfoot (NL)	H + C	IKEA store	-	-	2	200	1.4	-	-	-
Utrecht* (NL)	HT	University	1991	260	2	100	2.6	1.1	5	750
Amersfoot (NL)	H + C	Office building	1996	240	2	-	2	1.0	6.5	-
Oslo (NW)	H + C	Airport	1998	45	18	200	7	2.65	2	-
Zwammerdam* (NL)	HT	Hospital	1998	150	2	20	0.6	1.3	-	-
Berlin (DE)	H + C	Recihstag	1999	60/300	12	100/300	-	-	-	-
Rostock (DE)	H	District heating	1999	20	2	15	-	1.02	-	-
Amsterdam (NL)	H + C	District heating	2000	130	4	500	8.3	-	6	-
Brasschaat (BE)	H + C	Hospital	2000	65	2	100	1.2	0.7	8.4	427
Malmö (SW)	H + C	Expo building	2001	75	10	120	1.3	0.35	1.5	-
Mersin (TR)	C	Supermarket	2001	100	2	-	-	-	-	-
Agassiz (CA)	H + C	Research centre	2002	60	5	4	0.563	0.22	6	-
Eindhoven (NL)	H + C	University	2002	28-80	36	3,000	20	14.7	6-10	13,300
Malle ETAP (BE)	C	Office building	2003	67	2	90	0.6	0.34	7-15	23
Neubrandenburg (DE)	H	District heating	2005	1,200	2	100	3.3	-	-	-
New Jersey (US)	C	University	2008	60	6	272	2	2.6	12	-
Arlanda (SW)	H + C	Airport	2009	20	11	720	10	5.0	7	7,700
Copenhagen (DK)	H + C	Hotel	2009	-	2	-	2.4	-	6-7	366
Malmö (SW)	H + C	IKEA store	2009	90	11	180	1.3	-	4.5	-
Copenhagen (DK)	H + C	Office building	2010	100	10	250	2.8	-	4	644
Greenwich (UK)	H + C	Museum quarter	2011	60	2	45	0.33	-	-	-
Shinshu (JP)	H + C	University	2011	50	5	-	-	-	-	-
London (UK)	H + C	Apartments	2013	70	8	400	2.9	-	-	-
Amsterdam (NL)	H + C	District heating	2015	-	7	1,100	20	25.0	-	2,900
Copenhagen (DK)	H + C	Airport	2015	110	10	-	5	8.0	8	1,000

*** No longer in operation**

Table 4.2: Characteristics of aquifer thermal energy storage (ATES) installations. C = cooling; H = heating; HT = high-temperature. Source: Fleuchaus, P., Godschalk, B., Stober, I., & Blum, P. (2018). Worldwide application of aquifer thermal energy storage-a review. *Renewable and Sustainable Energy Reviews, 94*, 861–876.

largest LT-ATES system, at the Eindhoven University of Technology: a 36-well system (comprising 18 doublets) delivering 20 megawatts thermal of heating and cooling, with estimated annual CO_2 savings on the order of 13,300 tonnes.[79] Other LT-ATES deployments include universities, hospitals, airports, large commercial premises, domestic properties supplied via heat networks, and controlled environment agriculture (**Table 4.3**).

In addition, high-temperature ATES (HT-ATES) systems are also now being deployed, with storage temperatures on the order of between 40°C and 70°C.[80] At Delft University of Technology, an HT-ATES system currently being installed will operate in tandem with a deeper geothermal system supplying heat for direct use.[81] In summer, surplus heat from the geothermal system will be captured and stored by the HT-ATES system, while in winter, the deep geothermal and HT-ATES systems will both supply heating, meeting a larger proportion of total demand and reducing the load on the heat pump(s). A similar concept is being explored at the United Downs site in Cornwall, which would use mine thermal energy storage to store excess heat from the United Downs deep geothermal project as part of the EU-funded PUSH-IT (Piloting Underground Storage of Heat In Geothermal Reservoirs) project.[82]

Compared with the Netherlands, growth of ATES deployments in the UK has been slow. There are currently 11 known LT-ATES deployments, all located in England; nine are in London, one is in Brighton, and one is in Manchester.[83] The first ATES system was deployed in the UK in 2006 at a residential development in West London (**Table 4.3**). All but one of the operational ATES installations rely on the Chalk aquifer in London or Brighton; the system in Manchester utilises the Sherwood Sandstone aquifer. 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 and workspace, and part of a museum. Most installations deliver less than 1 megawatt thermal of heating and cooling via a single well doublet and are bivalent, supplying part of the heating and cooling demand. In most cases, peak

UK ATES INSTALLATIONS

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

Table 4.3: UK aquifer thermal energy storage (ATES) installations. kW_{th} = kilowatts thermal; m^3/h = cubic metres per hour. Source: Jackson, M. D., Regnier, G., & Staffell, I. (2024). Aquifer thermal energy storage for low carbon heating and cooling in the United Kingdom: Current status and future prospects. *Applied Energy, 376*, 124096.

cooling demand is larger than peak heating demand, highlighting the importance of supplying low-carbon cooling as well as heating.

The energy system at the Riverside Quarter in Wandsworth (**Table 4.3**) consists of an LT-ATES deployment that offers space heating and cooling to a large residential development, coupled with gas boilers and a combined heat and power engine for hot water and supplementary space heating. Supplementary space cooling is provided by dry air coolers.

Several of the early ATES deployments in the UK have ceased operation. The reasons are not always clear, but in at least one case the system operated despite a large imbalance in heating and cooling, leading to thermal breakthrough of the warm plume at the cool well and a rapid decrease in system efficiency.[84] In another UK system, there was a breakdown in communication between the ATES system engineers and building-side engineers, so the system operated for several years without being manually switched from heating to cooling mode when required, operating as a GWHP system with consequent impacts on plume formation and migration in the aquifer. Bivalent operation means shortfalls in heating or cooling delivered by UK ATES systems are met from other sources and may not be identified or diagnosed.[85] Failures of early deployments are typical of new technologies and have been recorded in ATES installations outside the UK.

Research and Development Needs

Research and development should focus on lowering barriers to widespread ATES deployment in the UK (**Table 4.4**). Key technical barriers include lack of knowledge of the subsurface and the likely subsurface response during system operation. Despite the availability of the open-loop GWHP mapping tool, previous studies characterising UK aquifer locations and properties and the availability of databases such as the BGS GeoIndex (Onshore), essential data are often unavailable or difficult to obtain for a potential installation site. Groundwater flow is a key control on thermal recovery efficiency but is not included in current mapping tools. Similarly, groundwater quality and chemical data are patchy. Mapping tools for ATES developed elsewhere include these data.[86] Easy access to geological maps, models, and borehole data is important to support the case for ATES in a particular location.

UK aquifers suitable for ATES deployment often offer high storage and productivity but are geologically heterogeneous, leading to uncertainty in subsurface groundwater flow, heat transport, and plume development (**Figure 4.8**). This uncertainty impacts predictions of optimal borehole spacing and thermal recovery efficiency. Well-characterised field experiments, such as thermal response tests (TRT) and open-loop thermal tracer tests (OL-TTT), provide key data and improved understanding of aquifer response. The recently opened UK Geoenergy Observatories' Cheshire Observatory offers a dedicated, at-scale field laboratory for research and innovation in ATES, rock volume characterisation, and monitoring of subsurface processes.[87] The observatory's borehole array penetrates the Sherwood Sandstone aquifer and is equipped with borehole heat exchangers for heating and cooling of the subsurface, advanced sensors for 3D imaging of subsurface processes in close to real time, and equipment for multilevel groundwater monitoring and hydraulic control. Current research, as part of the UK Research and Innovation–funded ATESHAC and SMARTRES projects, is undertaking both TRT and OL-TTT, coupled with extensive geophysical monitoring that is not available in commercial deployments. The tests provide new insights into groundwater flow and heat transport processes in the Sherwood Sandstone aquifer. Similar experiments targeting the Chalk aquifer are being undertaken at a test site in Berkshire as part of the SMARTRES project.

The geological heterogeneity of UK aquifers means that coupled thermal-hydrodynamic numerical models of appropriate resolution and complexity are required to predict the subsurface response during system operation, with extension to chemical transport and reaction if groundwater quality is an important consideration. These models are time-consuming and expensive to implement. The EU-funded FindHEAT project is developing new rapid methods for modelling geothermal reservoirs, including open-loop, shallow geothermal systems.[88] The rapid modelling research is led by UK institutions with the aim of supporting the deployment of geothermal by providing a new generation of agile modelling tools that reduce the time and cost of desktop studies.

The current focus of modelling in the UK is primarily to design and optimise the operation of individual developments, but as uptake of ATES and other shallow

BARRIERS TO WIDESPREAD DEPLOYMENT OF ATES IN THE UK

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 • Unfamiliarity in subsurface response
Societal barriers	• Lack of public awareness • Negative public perception of subsurface uses

Table 4.4: Many barriers are common to other emerging markets for ATES. Sources: Bloemendal, M., Hoekstra, N., Slenders, H., van de Mark, B., van de Ven, F., Andreu, A., Simmons, N., & Sani, D. (2018). *Europe wide use of sustainable energy from aquifers: Barrier assessment*. Deltares; Fleuchaus, P., Godschalk, B., Stober, I., & Blum, P. (2018). Worldwide application of aquifer thermal energy storage–a review. *Renewable and Sustainable Energy Reviews, 94*, 861–876; Pellegrini, M., Bloemendal, M., Hoekstra, N., Spaak, G., Gallego, A. A., Comins, J. R., Grotenhuis, T., Picone, S., Murrell, A. J., & Steeman, H. J. (2019). Low carbon heating and cooling by combining various technologies with aquifer thermal energy storage. *Science of the Total Environment*, *665*,1–10. Table from Jackson, M. D., Regnier, G., & Staffell, I. (2024). Aquifer thermal energy storage for low carbon heating and cooling in the United Kingdom: Current status and future prospects. *Applied Energy, 376*, 124096.

geothermal technology grows, predicting interactions between neighbouring installations will become increasingly important, especially in urban settings with high heating and cooling demand. Maximising the use of subsurface space is already a challenge in the Netherlands.[89,90,91,92] The UK has an opportunity to plan for high deployment density, but research is required to address the challenge of district- to city-scale optimisation of geothermal resource use.

Lack of awareness of, and confidence in, ATES technology and its suitability in the UK is also a key barrier to uptake.[93] A recurring issue in stakeholder discussions has been the lack of demonstrator projects with open access to data and the potential for site visits. Commercial deployments rarely make data available (the Riverside Quarter system is a rare exception), so successes are not shared, and there is little wider learning from failures. The UK urgently needs demonstrator and "living laboratory" projects for ATES and similar technologies. Potential candidates include the GeoEnergyNI shallow geothermal project at the Stormont Estate,[94] the University of Leeds Geothermal Campus Project,[95] and Imperial's plan to decarbonise its South Kensington campus in London.[96] However, at present, it is not clear whether these systems will include storage.

Liu et al. recognised slow turnaround for system permitting is another barrier to deployment.[97] Research into the subsurface response to ATES is essential to support permitting processes. Impacts on water quality, such as the potential for mixing of contaminants during operation, must be addressed.[98,99,100] Moreover, heat has recently been designated as a groundwater pollutant in the UK Environmental Permitting Regulations,[101] but the impact of temperature changes on storage aquifers remains poorly constrained. The SMARTRES project is currently assessing the impact of temperature changes induced by LT-ATES on the biochemistry of groundwater in the Chalk aquifer, but significant further research remains to be done, including for HT-ATES deployments in the UK.

Policy and Infrastructure Integration

Many of the policy and infrastructure integration issues impacting ATES are common with other shallow geothermal technologies. Key differences include (i) the high efficiency of cooling that can be delivered by ATES, and (ii) the importance of energy balance for sustainable ATES operation.

Policies encouraging the uptake of low-carbon technologies for heating and cooling have focused on heating. Cooling has been neglected, yet the importance of cooling for healthy living in a warming world is becoming increasingly apparent. Cooling demand in the UK, which is predicted to increase as a warming climate brings hotter summers, is already growing at a rate of 5% in London, the highest rate in the world.[102] Recent articles in the UK press have highlighted the challenges of living and working in buildings that are persistently too hot during the summer.[103,104] No mention is made of the potential deployment of technologies such as ATES that can offer low-cost cooling with low electricity demand and CO_2 emissions. Cooling and heating should be considered when developing policy. ATES systems that offer heating and cooling can be energy balanced, ensuring long-term sustainable operation. 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 that can negatively impact system sustainability.

Previous UK policy has incentivised heating and penalized storage. For example, under the now-discontinued Renewable Heat Incentive (RHI), "tariff payments for ground source heat pumps (GSHPs) can be made only for extracted heat that naturally occurs in the ground. As a consequence, heat that is injected into the ground and subsequently extracted by a GSHC system is ineligible for support payments."[105] Moreover, in the RHI scheme, "ground source and water source heat pumps that are capable of cooling are eligible technologies, though only heat generated is eligible for RHI support."[106] Incentives that support only heating and omit storage may instead encourage installation of systems with higher CO_2 emissions, which are less likely to be sustainable.

Delivery of both heating and cooling should also be accounted for in infrastructure integration. Building-site assessments often treat heating and cooling as separate processes with different solutions, consistent with the tradition of heating delivered by gas boilers and CHP plants and cooling delivered by electrical chillers. Heat networks also often consider heating but not cooling. A holistic view of heating and cooling when designing buildings and heat networks is required. Current UK ATES installations typically serve high-cost, luxury accommodation for which cooling is a marketing feature. There is an inequality of access to low-cost, low-CO_2 cooling that ATES could help address.

The aquifer requirements, borehole infrastructure, and surface facilities required for ATES and GWHC systems are similar; the main difference is in the mode of operation. GWHC systems can provide both heating and cooling with higher efficiency and lower CO_2 emissions than air source heat pumps (ASHPs) but are typically less efficient than ATES systems.[107] The additional efficiency and lower electrical grid requirements offered by storage and re-use of thermal energy—especially for cooling—suggest that ATES should be considered ahead of GWHC when considering an open-loop geothermal deployment for both heating and cooling. A balanced ATES system should be considered ahead of a GWHP system when possible.

The policy and regulatory frameworks for ATES in the Netherlands are an attractive model for the UK and other emerging markets.[108,109] The Geo-Energy Systems Amendment in the Netherlands features a simplified permit process, which normally has a maximum decision period of eight weeks (see more in Chapter 5, "Clearing the Runway: Policies and Regulations to Scale the United Kingdom's Geothermal Potential"); company certifications to ensure high system quality; and standardised system monitoring requirements. The regulations specify upper and lower storage temperature limits of 25°C and 5°C, respectively, and the requirement for energy balance. The Dutch have introduced geothermal energy master plans for coordinated spatial subsurface and energy planning of ATES systems in dense urban areas. An interactive

WANDSWORTH RIVERSIDE QUARTER, LONDON—AQUIFER THERMAL ENERGY STORAGE IN THE CHALK

Figure 4.9: (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: Jackson, M. D., Regnier, G., & Staffell, I. (2024). Aquifer thermal energy storage for low carbon heating and cooling in the United Kingdom: Current status and future prospects. *Applied Energy, 376*, 124096. Modified from IF Tech. (2008). *Wandsworth Riverside Quarter, London: Borehole drilling and pumping tests.* IF Tech.

online map by the Dutch Ministry of Economic Affairs and the Ministry of Climate Policy and Green Growth allows municipalities to mark designated areas for geothermal use, aiding ATES planning.

Case Study: Wandsworth Riverside Quarter, London—Aquifer Thermal Energy Storage in the Chalk

The Wandsworth Riverside Quarter (WRQ) residential development in south-west London hosts one of the UK's largest operational ATES schemes.[110,111] The project shows how open-loop, seasonal storage can provide low-carbon heating and cooling to dense urban developments in a fractured Chalk aquifer as opposed to the sandy aquifers more commonly used for ATES across Europe.

Primary Goal and Delivery Model

WRQ's energy system was designed under the London Plan policy framework in force at the time, which promoted on-site low-carbon energy and set minimum CO_2-reduction targets. ATES supplies space heating and cooling; gas boilers and a CHP engine provide domestic hot water and top-up heat; and dry-air coolers are available for supplementary cooling. Controls are configured to redistribute waste heat and cool around the estate before drawing on the aquifer.

Scheme Configuration (Subsurface and Plant)

- **Aquifer and geology:** Eight production/injection wells target the Upper Chalk, first encountered at approximately 79 metres depth; the aquifer is confined by London Clay. Local records indicate the Thanet Sands and Woolwich & Reading Beds are absent at the site. Groundwater flow in the Chalk is fracture-dominated (high matrix porosity, low matrix permeability).
- **Wellfield:** Four warm and four cold wells drilled to between 113 metres and 143 metres below ground level; post-drill flow logs show that most inflow or outflow occurs within the upper approximately 15 metres of the Chalk, with a high-permeability interval at around 80 metres to 82 metres, consistent with prior London Chalk studies.
- **Licensed capacity and plant:** Maximum licensed abstraction = 280 cubic metres per hour. Design capacity = 1.8 megawatts thermal heating and 2.7 megawatts thermal cooling. Two reversible heat pumps serve both modes.

Operations and Measured Performance

- **Monitoring window:** Hourly wellhead flow rate and temperature data from 2015–2022 are available (system in service since 2013). The data set shows the expected seasonal cycling (warm production in winter/cold injection; the reverse in summer).

- **Energy and volume balance (sustainability):** Over the monitoring period, the energy balance ratio is 0.09—cooling energy extracted is approximately 20% greater than heating energy—while the volume balance ratio is -0.03, indicating similar total pumped volumes in both modes. These metrics indicate sustainable, near-balanced operation; the installed dry-coolers could be used to correct any future imbalance.
- **Key monitored means (annual averages)**:
  - Injection = 9.8°C (cold)/22.2°C (warm); production 12.6°C (cold)/17.6°C (warm)
  - Active production flow = 14.4 cubic metres/ hour (cold)/13.8 cubic metres per hour (warm)
  - Annual volumes produced = ~46,600 cubic metres (cold)/~48,900 cubic metres (warm)
  - Annual energy produced at the aquifer/HEX: ~508 MWh_{th} cooling/~424 MWh_{th} heating
- **Thermal recovery (storage efficiency):** For 2015–2021, average thermal recovery was approximately 30% (warm) and around 16% (cold), increasing over time as the field matured. Recovery was lower than values typically reported from more homogeneous sandy aquifers, reflecting the fractured Chalk and associated lateral "pancake" plume spreading. Using an effective screen length concept to represent the shallow inflow zone, modelling indicates that if the effective screen length is less than 5 metres, thermal interference between warm and cold plumes becomes likely at the site's minimum warm–cold spacing of 127 metres; less than 1.5 metres risks short-circuiting. Flow logs suggest approximately 2 metres of inflow, so some interference may occur.
- **Delivered energy and carbon:** Delivered low-carbon energy averaged approximately 0.49 gigawatts thermal per year cooling and approximately 0.39 gigawatts thermal per year heating between 2015 and 2021, rising with recovery. Values were lower than some schemes of similar design capacity due to operational flow rates below licence and the site's strategy to maximise internal heat and cool redistribution before drawing on the aquifer. From Year 2 onward, the WRQ system saved more than 100 tonnes of CO_2 per year versus a natural-gas reference; savings should grow with continued grid decarbonisation.

Lessons for Policy and Investors

- **Demonstrated viability in fractured aquifers:** WRQ proves that balanced, monitored ATES can operate successfully in the Chalk, widening the UK deployable footprint beyond sandy aquifers. Seventy-five percent of the UK population resides over these types of aquifers, opening up large parts of the country to deploy this low-carbon heating and cooling method.
- **Importance of monitoring and balance:** Routine capture and interpretation of flows, temperatures, energy balance ratio and volume balance ratio, and recovery enable early issue detection and underpin sustainable operation; the authors recommend explicit identification of ATES in regulatory databases and enforcement of energy balance in licences.
- **Design for heterogeneity:** Well spacing and effective screen length govern plume geometry and interference risk in fractured media; flow-log-informed screen design and conservative spacing (such as multiples of the thermal radius) mitigate losses.
- **Market context:** WRQ is one of approximately 11 active ATES deployments in the UK, the majority of which are in London—highlighting significant scale-up potential with clearer guidance and streamlined permitting.

WRQ offers a bankable, real-world precedent for urban ATES in UK geology that is heterogeneous and fracture-controlled—delivering dependable low-carbon heating and (especially) cooling while providing the monitoring evidence that policymakers and investors need to manage subsurface risk and scale the sector responsibly

Scaling Up Geothermal Heat

The United Kingdom's current geothermal heat projects reveal three key insights for policymakers, investors, and planners:

1. **Technical feasibility is proven.** Across diverse geological contexts from deep sedimentary aquifers to minewater systems and thermal spring discharges, reliable year-round heating and cooling can be delivered using mature and adaptable technologies.

2. **Integration drives resilience.** Each scheme combines geothermal baseload with complementary technologies such as heat pumps, waste heat recovery, combined heat and power (CHP), and district heating, resulting in flexible, robust energy systems.
3. **Governance and planning are critical.** Long-term customer contracts, anchor public-sector loads, supportive planning frameworks, and emerging heat network zoning policies underpin the bankability of these schemes. (See Chapter 5, "Clearing the Runway: Policies and Regulations to Scale the United Kingdom's Geothermal Potential," for more on this topic.)

Geothermal heating projects that are already operational, monitored, and delivering quantified carbon savings provide a scalable pathway for reducing emissions from heating and cooling, one of the UK's most energy-intensive sectors. With coordinated investment, clearer regulatory frameworks, and strategic policy support, the Bath, Gateshead, Wandsworth, and Southampton schemes could form the blueprint for a national geothermal heat strategy. By embracing these models, the United Kingdom can accelerate progress towards resilience, enhance energy security, safeguard heritage assets, and drive regional economic growth, establishing geothermal energy as a key enabler of sustainable heating and cooling.

MINEWATER GEOTHERMAL ENERGY IN THE UK

Target Areas

Minewater geothermal energy exploits the heat stored in flooded, disused mines. The UK's industrial legacy (23,000 abandoned mines, primarily but not exclusively for coal[112]) has left an extensive subsurface network of shafts and galleries—many of which have filled with groundwater. This water retains geothermal heat and offers a large, distributed, low-temperature resource ideal for direct-use heating applications.

Many of these flooded mines are located under, or close to, residential and industrial developments. Approximately 25% of the UK population lives above abandoned coalfields (**Figure 4.10**), which could theoretically be harnessed to provide 2.2 million gigawatts of heat, enough to heat all of the UK's houses for more than 100 years.[113] According to a combined study from the Ordnance Survey and the Mining Remediation Authority (formerly the UK Coal Authority), this means just more than 6 million homes, and more than 300,000 offices and businesses, are above abandoned coal mines and could be heated by this resource.[114]

> ***Approximately 25% of the UK population lives above abandoned coalfields, which could theoretically be harnessed to provide 2.2 million gigawatts of heat, enough to heat all of the UK's houses for more than 100 years.***

Regions with the most extensive minewater geothermal potential include the South Wales Coalfield, central Scotland (including Glasgow and Lanarkshire), north-east England (such as Durham and Northumberland), the East and West Midlands, Lancashire, and Kent in the south of England. In Northern Ireland, disused mining areas such as East Tyrone (Dungannon–Coalisland) and Ballycastle also have potential for minewater heating, albeit on a smaller scale and with more localised resources (**Figure 4.10**).

System Characteristics and Mechanism

Former coal and mineral mines across the UK present a significant opportunity for geothermal energy development by exploiting the natural geothermal gradient—where temperatures increase with depth. Minewater at depths of up to 1 kilometre can reach temperatures of 40°C (recorded in the Lancashire coalfield),[115] although such levels are unlikely to be sustained once pumping starts. More commonly, flooded mines provide a stable reservoir of water with temperatures typically ranging from 12°C to 49°C (as measured in Plodder and Arley mines in Leigh and Tyldesley Lancs),[116] which can be upgraded using heat pumps. These can supply low-temperature heating systems (40°C–70°C) and provide cooling and thermal storage. Unlike deep geothermal systems, minewater schemes operate at relatively shallow depths, commonly between around 50 metres and 400 metres (**Figure 4.11**), thereby significantly reducing both drilling costs and lifting costs for the water during the production phase.

A typical system includes an abstraction well to pump warm minewater to the surface, a heat exchanger and

DISTRIBUTION OF ONSHORE COALFIELDS, MINERAL MINES, AND DISTRICT HEATING DEMAND ACROSS THE UNITED KINGDOM

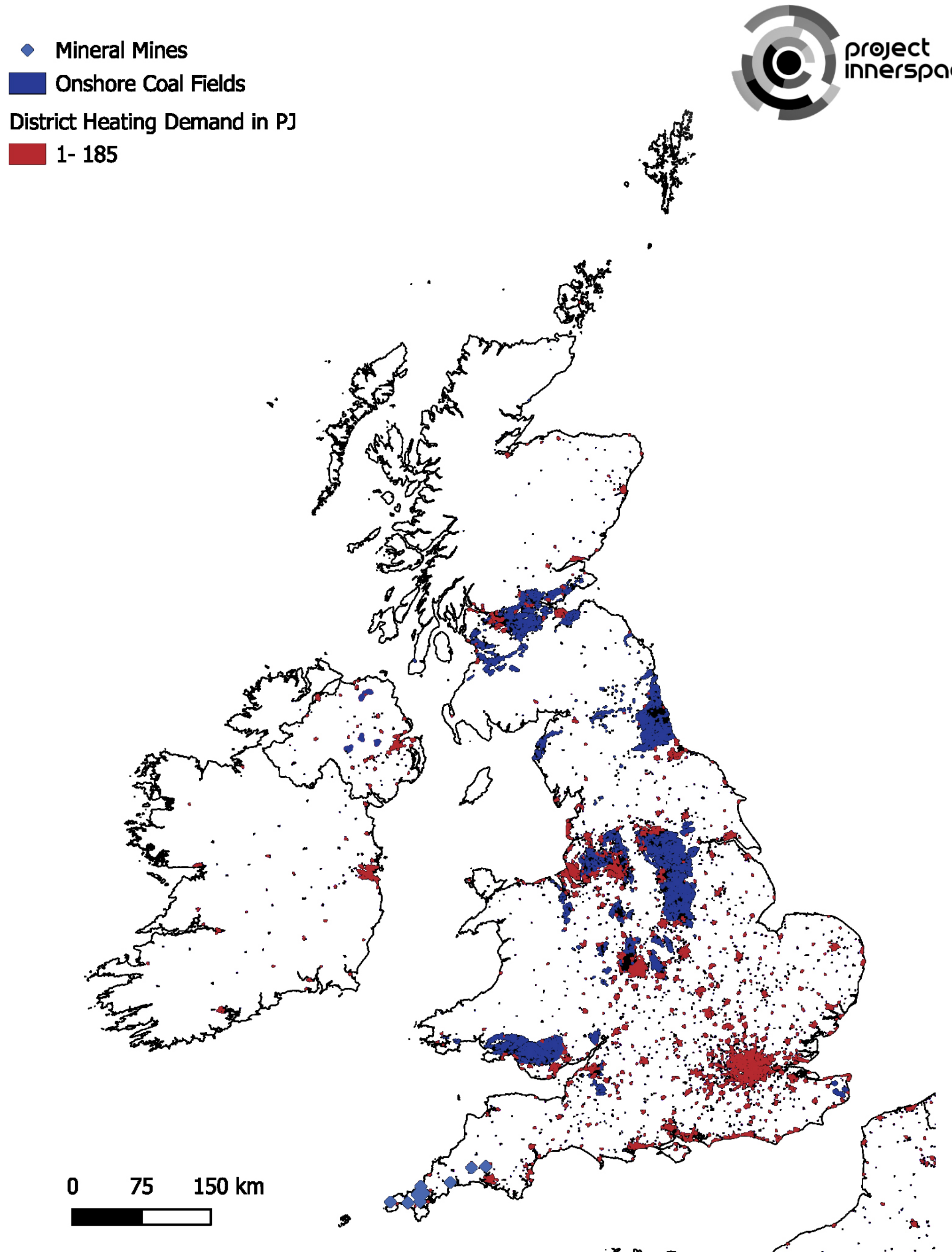


Figure 4.10: Distribution of onshore coalfields, mineral mines, and district heating demand across the United Kingdom. Areas shaded in pink indicate known onshore coalfields, while red diamonds mark the locations of active or historical mineral mines. Purple dots show spatial variation in district heating demand (1–185 PJ), highlighting significant clusters of potential heat users in urban and industrial regions. This spatial overlap informs the assessment of minewater geothermal and co-located geothermal heating opportunities. Data sources: ArcGIS Hub. (2025). Mineral mines. *UNESCO WHC sites dossiers elements core points;* Fleiter, T., Manz, P., Neuwirth, M., Mildner, F., Persson, U., Kermeli, K., Crijns-Graus, W., & Rutten, C. (2020). *Documentation on excess heat potentials of industrial sites including open data file with selected potentials* (Version 2). Zenodo; Onshore coal fields available from OGL, British Geological Survey. (2020). *Coal resources for new technologies dataset*. Contains British Geological Survey materials © UKRI 2025. Projection: OSGB36 / British National Grid.

INFLUENCES ON HEAT TRANSFER IN MINEWATER SYSTEMS

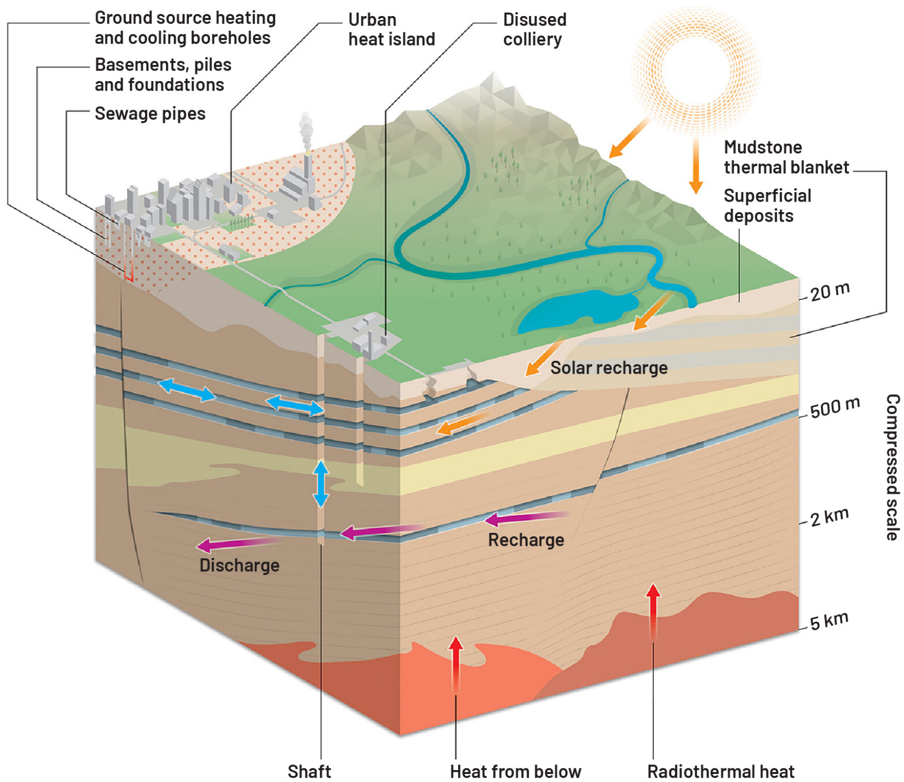


Figure 4.11: Block diagram showing predominant heat sources and variations influencing heat transfer in minewater systems. Red arrows represent conductive processes; blue arrows represent groundwater flow in mines and shafts; orange arrows are indicative of heat transfer via solar recharge; purple arrows represent regional groundwater flow, recharge, and discharge across the mined rock volume. Source: BGS for © Coal Authority 2022, published in Monaghan, A. A., Adams, C. A., Bell, R. A., Lewis, M. A., Boon, D., González Quirós, A., Starcher, V., Farr, G., Wyatt, L. M., Todd, F., Walker-Verkuil, K., MacAllister, D. J., Abesser, C., Palumbo-Roe, B., & Scheidegger, J. (2026). Geological factors in the sustainable management of mine water heating, cooling and thermal storage resources in the UK. *Energy Geoscience Conference Series, 1*, egc1-2023-39.

heat pump to transfer heat to a distribution network, and a reinjection well to return the cooled water back into the mine system—albeit into a different mined level (seam) and/or at a distance from the production well to avoid it mixing with the warmer water being extracted. Although open-loop systems are typically used, closed-loop systems can also work in mines.[117,118,119]

UK Activity

The Mine Remediation Authority plays a key role in permitting and licensing minewater energy developments in the UK. It supports more than 20 minewater heating investigations across the country, providing access to historic and current data; borehole design guidance; and technical advice for local authorities, utility providers, and developers. This support will help build a robust knowledge base and de-risk future projects.

North-east England has seen the greatest amount of progress with large-scale schemes (megawatt thermal scale) already operational at Lanchester Wines and Gateshead.[120,121] The Gateshead minewater heat network, operational since March 2023, is the largest of its kind in Great Britain and among the largest in Europe. It extracts heat from minewater 150 metres beneath the town centre using a 6 megawatt heat pump and a 5 kilometre heat network, supplying homes, public buildings, and commercial facilities. The project is estimated to save 72,000 tonnes of CO_2 over 40 years.[122]

The Seaham Garden Village in County Durham is a domestic-scale scheme in development that is expected to heat at least 1,000 homes with minewater from an existing treatment site. Estimated carbon savings are 2,600 tonnes of CO_2 annually over a 25-year period.[123]

In Wales, the Lindsay scheme in Carmarthenshire is one of the first to supply heat to a commercial facility using submerged heat exchangers in a minewater treatment pond. Funded by Innovate UK, it supports decarbonisation of local industry and serves as a model for future undertakings.[124]

A similar test scheme in Bridgend, Wales, explored the feasibility of using minewater for heating. Initiated in 2016, the project aimed to harness geothermal energy from the flooded former Caerau Colliery to supply heat to approximately 300 homes, as well as community buildings and a primary school.[125] However, the development was discontinued due to significant technical and commercial uncertainties encountered during the design and planning stages. This project highlights the complexities and challenges involved in implementing minewater heating schemes in the UK.

In Scotland, two historical schemes investigated the use of minewater, one at Shettleston in east Glasgow and one at Lumphinnans in Fife, though neither are currently operational.[126] The Shettleston project in Glasgow, completed in 1999, is an early example of an open-loop ground source heat system using minewater. It served 16 dwellings (houses and flats), drawing water at 12°C from flooded coal mine workings (probably in the Glasgow Ell Seam) via an approximately 100 metre-deep borehole. The Lumphinnans project in Fife, completed in 2000–01, was an open-loop ground source heat system retrofitted to a 1950s apartment block of 18 dwellings. Minewater was pumped from flooded coal workings in the Jersey/Diamond seam via a 172 metre-deep borehole, with reported temperatures of between 12°C and 14.5°C.[127] The system at Lumphinnans experienced problems caused by air entering into the reinjection borehole, leading to clogging of the borehole with precipitation of ochre (ferric oxyhydroxide). Shettleston operated trouble-free for at least 10 years, but the costs and logistics of necessary maintenance proved challenging for the social housing operator, which was one reason it failed. A backup gas system was installed to ensure heat could be delivered continuously to residents, and the gas system effectively displaced the minewater heating.

In Northern Ireland, the East Tyrone Coalfield contains workings up to approximately 280 metres deep and has potential for small-scale schemes (subject to further exploration).[128] The Ballycastle Coalfield is shallower and less prospective, but it still offers potential for low-capacity heat extraction, particularly in rural and coastal areas.

Many existing developments in the UK are supported by the Mining Remediation Authority, which also permits access to mine workings and collaborates on research with academic partners. The Gateshead Living Laboratory provides a unique environment for monitoring thermal and hydrogeological behaviour in a real-world setting. This complements research at the Glasgow Observatory, part of the UK Geoenergy Observatories programme, which advances knowledge of shallow geothermal systems and minewater heat extraction.

BGS is also actively engaged in mine geothermal energy and thermal storage research, including the EU-funded PUSH-IT project.[129]

Together, these initiatives demonstrate the UK's growing capacity to harness clean energy from abandoned coalfields, offering a scalable, low-carbon solution for heating buildings and decarbonising heat networks.

Applications and Use Cases

The primary applications of minewater geothermal systems include urban heat networks in former coalfield communities, as well as low-temperature heating for residential housing, schools, municipal buildings such as warehouse storage (Abbotsford and Nest Roads, Lanchester Wines scheme in Gateshead), leisure centres, and industry. Constant-temperature minewater can also be used for greenhouse and aquaculture heating. Additionally, these systems support cooling through reverse-cycle operation and can facilitate seasonal thermal energy storage (see "Underground Thermal Energy Storage in the UK, with a Focus on Aquifer Thermal Energy Storage").

Key advantages include relatively shallow drilling requirements, low-carbon intensity, and a strong spatial correlation between the resource and areas of socio-economic need, such as those affected by fuel poverty. Observations in the Durham Coalfield indicate that residents welcome such schemes, which are seen as positive legacies of a mining heritage.[130] Many UK towns were developed in areas with coal, and homes in such areas were built in vast numbers. Minewater systems are also well suited for integration with low-temperature district heating infrastructure.

An illustrative example is the Heerlen Mijnwater Project in the Netherlands, a geothermal initiative that originated from the European Interreg IIIB NWE programme and the Sixth Framework Programme project EC-REMINING-lowex. The Mijnwater project has been operating since 2008 and was developed as a fourth-generation district heating and cooling network.[131] During winter, warm water (28°C) is extracted from former mine workings and fed into the network to supply heat. In summer, cooler water (16 °C), drawn from shallower sources, is circulated to provide cooling.

By 2020, Mijnwater was supplying sustainable heating and cooling to more than 400 dwellings and 250,000 square metres of commercial buildings. The project makes a significant contribution to the sustainability of the built environment in Heerlen and the wider Parkstad Limburg region. It also plays a key role in positioning Heerlen as an innovative green tech hub in the field of thermal smart grids. The long-term objective is to connect 30,000 homes and offices in Parkstad by 2030.[132]

Lessons Learnt and Next Steps for Minewater Geothermal Resource Assessment in the UK

The exploration and development of minewater geothermal systems in the UK present technical and operational challenges, but minewater geothermal remains one of the most advanced and promising geothermal technologies. With the potential to deliver sustainable, low-carbon heat to economically disadvantaged communities, minewater schemes are attracting more attention. A critical requirement is demonstrating the long-term stability of heat output to build confidence among stakeholders and investors. The Seaham Garden Village project is a leading example, as decades of continuous mine dewatering, treatment, and disposal have already demonstrated the resource's reliability and sustainability. Ongoing monitoring and maintenance are essential to ensuring success, including continuous tracking of key parameters such as temperature, groundwater levels, flow rates, and water quality. Minewater geothermal projects face several technical risks, the most significant of which relate to siting, hydraulics, and water chemistry. Siting risks arise from uncertainty in historical mine plans, which can result in exploratory boreholes missing target voids. Hydraulic behaviour is often unpredictable, with abstraction and reinjection sometimes showing contrasting responses even within the same seam. Water chemistry presents another critical challenge, with oxygen ingress leading to clogging and scaling and dissolved gases such as methane or hydrogen sulfide creating safety and materials issues. These risks vary in their implications. Some, such as siting uncertainty, mainly affect upfront drilling costs, while others, such as clogging or gas hazards, can pose long-term operational and maintenance challenges. Many of these risks are well understood and can be mitigated through established engineering practices, such as phased exploration, sealed pressurised systems, appropriate material selection, and proactive maintenance planning. (**Table 4.5** provides a breakdown of potential risks and case examples.)

Steps to Ensure Minewater Geothermal Energy Schemes Can Be Scaled in the UK

Minewater geothermal energy schemes (MGES) are an emerging innovation both in the UK and globally, with each system presenting its own location-dependent and project-specific characteristics, which can make replication and upscaling challenging. There is no universal framework for assessing, monitoring, and governing minewater geothermal resources, either independently or in hydraulic and thermal communication with one another. There are also significant gaps in our ability to assess the technical viability and environmental sustainability of MGES in urban centres, where

SUMMARY OF KEY RISKS

Risk Area	What Could Go Wrong (Mechanism)	Illustrative Cases	Typical Mitigations	References
Hitting the target (siting)	"Striking open workings" is uncertain, especially where mine plans are old; exploratory drilling may miss mapped voids or hit unmapped ones.	**Nest Road, Gateshead (UK):** Four boreholes were needed to get one good abstraction and one good reinjection borehole.	Allow contingency drilling; use phased exploration; use multiple horizons to increase chances of connectivity.	Walls et al., 2021; Banks, 2021
Unpredictable hydraulics	Abstraction and reinjection in different seams within the same area can show very different responses.	**Nest Road:** Abstraction showed flat drawdown (good connectivity); deeper reinjection behaved like a "sealed reservoir."	Treat models with caution; be prepared for unconventional hydraulic responses; test both production and injection.	Walls et al., 2021; Banks, 2021
Geotechnical stability	Rapid pressure changes or high flows in shallow workings may risk instability or erosion of pillars.	The UK Mining Authority typically requires geotechnical assessment.	Conduct geotechnical risk assessment; use conservative ramp-up; monitor.	Walls et al., 2021; Todd et al., 2019
Inadequate yield or injectivity	Poor void connectivity or chemical/biological clogging of reinjection wells (often from oxygen ingress) lowers capacity.	**Lumphinnans (Scotland):** Free-cascading injection promoted iron oxidation, which led to clogging, which contributed to cessation.	Eliminate free fall into reinjection wells; use pressurised sealed abstraction-heat exchange-reinjection systems; maintain anoxic conditions; wells and other pipework/heat exchangers may need regular maintenance.	Walls et al., 2021; Banks et al., 2009; Banks et al., 2017; Walls et al., 2020
Dissolved gas hazards (hydrogen sulfide [H_2S] and operational)	O_2 ingress oxidises Fe/Mn → ochre; CO_2 degassing raises pH → scaling; asphyxiation risk in enclosed spaces; methane and H_2S require control.	**Markham No. 3 (UK):** methane deliberately vented **Nest Road:** Reducing, H_2S-rich water corroded downhole sensors.	Anoxic, pressurised abstraction-heat exchange-reinjection systems; handling; ventilate/flare methane; gas monitoring; materials compatible with H_2S/CO_2.	Walls et al., 2021; Gunning et al., 2019; Steven, 2021; Banks et al., 2017; Banks et al., 2009; Hill, 2004
Clogging and scaling	Mobilised fines and ochre (ferric oxy-hydroxides) foul filters, heat exchangers and wells; filters can become a "locus for ochre."	**Mieres (Spain):** Mineral grains were found in disassembled plate heat exchanger; widespread ochre issues were noted.	Anoxic, pressurised abstraction-heat exchange-reinjection systems; staged filtration with easy service; periodic chemical/mechanical cleaning; conservative velocities.	Walls et al., 2021; Loredo et al., 2017
Corrosion	Acid generation and elevated "free" CO_2 corrode carbon/mild steels; H_2S accelerates corrosion (even in some stainless steels). Sensors at Nest Road were replaced with titanium.	**Nest Road:** H_2S-related sensor corrosion; general CO_2/H_2S corrosion literature applies.	Material selection (plastics, titanium, high-alloy where justified); control O_2/CO_2 ingress; biocide where appropriate.	Walls et al., 2021; Steven, 2021; Twigg, 1984; Koteeswaran, 2010; Li et al., 2019
Treatment and discharge constraints	Meeting Fe/Mn (UK) or salinity limits may require treatment, if thermally "spent" minewater is to be returned to the surface environment; using "treated" (oxygenated) water in heat exchange systems can trigger fouling.	**Dawdon (UK) pilot:** minewater treated by aeration and settlement to remove iron. This introduced oxygen to the water. Residual iron rapidly oxidised and clogged components of the heat exchange system. The system was redesigned to use anoxic, untreated water.	Use anoxic, pressurised abstraction-heat exchange-discharge systems; monitoring will usually be required to demonstrate that the water quality and temperature of any discharge to the surface environment comply with environmental regulations.	Walls et al., 2021; Banks & Banks, 2001; Loredo et al., 2017; Bailey et al., 2013

SUMMARY OF KEY RISKS (CONTINUED)

Risk Area	What Could Go Wrong (Mechanism)	Illustrative Cases	Typical Mitigations	References
Thermal feedback and interference	Short flowpaths or same-seam doublets can cause cold-front breakthrough; multiple schemes risk mutual interference.	**Tyneside (UK):** Nest Road and Abbotsford Road are ~700 m apart—no clear evidence of thermal conflict to date.	Different mined horizons for abstraction and reinjection; design for long/tortuous flowpaths; monitoring.	Walls et al., 2021; Banks, 2021; Steven, 2021
Pumping head and parasitic load	Deep dynamic heads and pipe losses increase pump energy, resulting in lower system COP and poorer economic outcomes.	Discussed in general and with Markham context.	Minimise lift and frictional losses; do not unnecessarily oversize pumps site energy centres near source; use gravity assists or standing-column where feasible.	Walls et al., 2021; Banks et al., 2017
Demand, permitting, and future availability	Demand density may be insufficient even if resource is good; permits can miss delivery windows; resource access can be lost if pumped/gravity discharges are moved, cease pumping, or dry up.	**Fortissat (Scotland):** technically favourable, demand density insufficient. **Fordell Castle (Scotland):** gravity discharge reportedly dried due to opencast at Muirdean.	Early stakeholder work with operators and regulators; lock-in discharge points; pair schemes with anchor loads (district heating).	Walls et al., 2021; Harnmeijer et al., 2017; Government of the United Kingdom, 2021; Sparling, 2013
Operations and maintenance (O&M) burden (small schemes)	"Accumulated ongoing monitoring and maintenance burdens" can make small and medium systems uneconomical; recurring reinjection/heat-exchanger fouling.	**Shettleston (UK):** long-running scheme ultimately decommissioned, probably due to ongoing financial and logistical challenges of maintenance.	Planned access and budgets for cleaning and descaling; budget for proactive maintenance; favour scale where O&M is economical.	Walls et al., 2021; Banks et al., 2009

Table 4.5: Summary of key risks for minewater geothermal in the UK. Full source list can be found after the conclusion to this section.

assessment and monitoring may be challenging and where one minewater resource may straddle multiple minewater access agreement (MAA) areas. To ensure resilience and environmental sustainability at scale, scalable modelling within the subsurface must be improved in a way that supports operational and planning decisions. To achieve this goal, the UK would need to address the following interdependent issues:

- **Obstacles to at-scale implementation:** high capital expenditures and long payback period; high operational expenditures (non-standardised operation and maintenance); possibly complex to retrofit; no legal or financial framework for heat ownership and sales; low level of customer buy-in; short-, medium-, and long-term liabilities; clogging, scaling, and corrosion of equipment; water treatment requirements; availability of skilled workforce and at-scale supply chain.
- **Potential impacts on social and community key performance indicators:** energy poverty; limited stakeholder engagement; need to shift from passive to active energy citizenship and community "ownership" of low-carbon heating and cooling interventions; risk vs. benefit perception and acceptance; real vs. perceived risks; lack of inclusion of social key performance indicators in energy system models.
- **Subsurface characterisation uncertainties:** geological controls; conditions and geometry of abandoned mineworkings; fluid chemistry; geomechanical stress regime; presence of natural or mining-induced fractures and their transmissibility; fluid/heat pathways; aquifer recharge; natural geothermal gradient vs. anthropogenic heat; subsurface urban heat islands.
- **Understanding dynamic system response:** coupled Thermal-Hydrological-Mechanical-Chemical processes over project life cycle; hysteresis of petrophysical and geomechanical controls; mixing dynamics during pumping; minewater rebound; interference between boreholes in and between MAAs.

- **Potential environmental impacts:** uncontrolled emissions of gas and water; altering water table depth and groundwater-surface water interactions; thermal impacts on aquifer in addition to climate change and urbanisation; chemical impacts such as homogenisation of natural vertical quality gradient; microbiological impacts altering aqueous ecosystem.
- **Potential impact on land and adjacent properties:** subsidence; collapsed mineworkings; induced seismicity; increased heating demand in buildings above cooled subsurface; contamination of groundwater at downstream sites; increased frequency of groundwater flooding jointly with climate change.
- **Limited prospect evaluation experience:** no established MGES "geothermal play" catalogue or "analogue field" concept for initial assessment of resource potential.
- **Unsuitability of conventional exploration methods:** inability to use large-scale 3D geophysical investigations in a built environment; constrained vibroseismic measurements near properties that lack foundations; sensor interference with ground-borne urban noise.
- **Need for both project-level and minewater block-level monitoring:** land accessibility inside/outside MAA area; costs of distributed measurements; requirements for ad hoc spatial and temporal

Table 4.5 sources

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resolution; no standards to review and grant adjacent MAAs within a given minewater block.

- **Limitation of modelling capabilities:** no "standard" approach to modelling dynamic MGES performance over project lifetime; primary focus so far on Thermal-Hydrological rather than Mechanical-Chemical processes, and 1D/2D rather than 3D.

Case Study: Gateshead Minewater District Heating Scheme

The town of Gateshead, located in north-east England, has embarked on one of the UK's most ambitious minewater district heating schemes. Led by Gateshead Council and its energy company, this project exemplifies the potential of minewater energy to supply clean, affordable heat to post-industrial communities.[133,134]

The primary goal of the scheme is to reduce carbon emissions and heating costs for local residents and public buildings while demonstrating a scalable model for other former coalfield areas in the UK.[135] Two megawatt-scale, low-enthalpy minewater geothermal heat pump schemes have already been developed in the Gateshead Area, Tyneside, at Abbotsford Road and Nest Road. These are used for low-carbon heating of

GEOLOGICAL MAP OF THE FELLING AREA, GATESHEAD

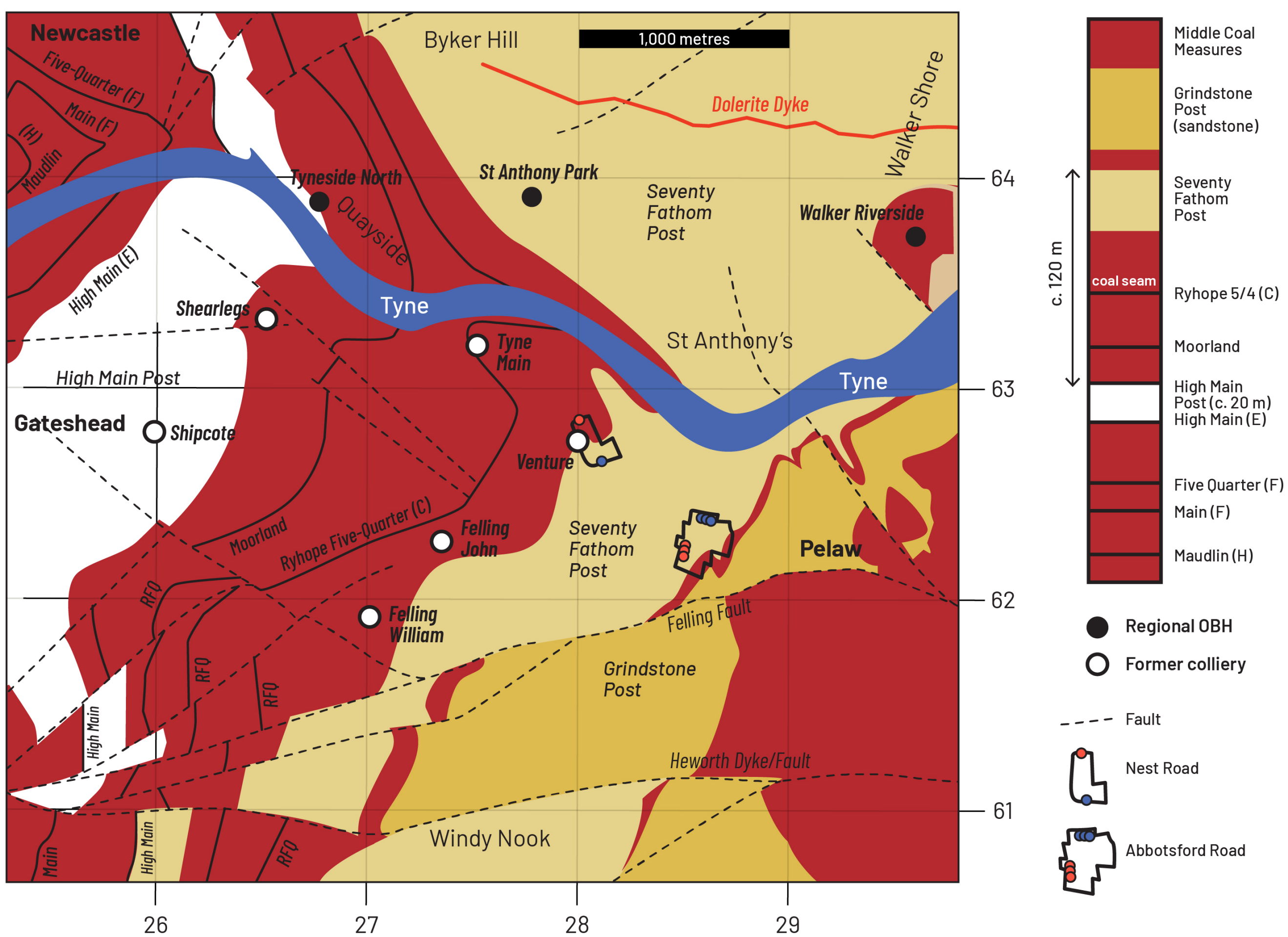

Figure 4.12: Simplified geological map of the Felling area, Gateshead, showing regional Observation Boreholes (OBH). Geological information derived from British Geological Survey (https://www.bgs.ac.uk/, accessed on 25 November 2021) mapping. Contains Open Geoscience public sector information licensed under the Open Government Licence v3.0. Source: Banks, D., Steven, J., Black, A., & Naismith, J. (2022). Conceptual modelling of two large-scale mine water geothermal energy schemes: Felling, Gateshead, UK. *International Journal of Environmental Research and Public Health, 19*(3), 1643.

wine warehouses; their status as of around 2022 was as follows:[136]

- **Abbotsford Road** scheme has typically abstracted between 20 litres per second and 30 litres per second of groundwater from the unmined Coal Measures upper aquifer system (UAS), extracting heat before reinjecting the cooled water into the an aquifer system associated with the High Main (E) coal workings and the overlying High Main Post sandstone (the High Main Aquifer System, or HMAS; see **Figure 4.12**).
- **Nest Road** scheme is located about 700 metres to the north-west of Abbotsford Road. This scheme abstracts 40 litres per second from the HMAS, recovers heat, and reinjects thermally spent water into deeper workings linked to the Hutton (L) and Harvey-Beaumont (N) coal seams, as well as possibly other seams. This deeper network is termed the deep mined aquifer system (DMAS; see **Figure 4.12**).

The UAS, HMAS, and DMAS are vertically discontinuous aquifer systems with distinct hydraulic properties (storage, transmissivity, and connectivity), which would have been extremely difficult to predict prior to drilling. Across both sites, 10 boreholes were drilled to secure five usable production and reinjection boreholes.[137]

Operational since March 2023, a 6 megawatt water source heat pump recovers heat and distributes it via a network of heat network pipes more than 5 kilometres long. This network currently serves more than 350 homes, as well as Gateshead College, the BALTIC Centre for Contemporary Art, the Glasshouse, GB Lubricants, and local commercial offices. There are plans to expand supply to an additional 270 homes, a conference centre, and a hotel.[138] This project has an estimated savings of 72,000 tonnes of CO_2 over 40 years, or about 1,800 tonnes of CO_2 per year.[139]

In 2024, Gateshead Council was awarded £5.9 million in Heat Networks Investment Project funding to install 5 kilometres of new heat network pipes, boreholes, and an energy centre, enabling access to 6 megawatts of minewater heat.[140] It has been developed through partnerships involving Gateshead Energy Company, the Mining Remediation Authority (previously the Coal Authority), BGS, GEA, Balfour Beatty, and local research institutions.

In early 2025, and in agreement with Gateshead Council, the Mining Remediation Authority launched a Living Laboratory adjacent to the heat scheme.[141] This research initiative includes additional boreholes, extensive sensor installations, and open-access data tools to monitor and model the hydrogeological and thermal performance of the minewater system in real time, as well as its interaction with neighbouring minewater thermal schemes. The Living Lab is intended to support improved modelling, risk management, and regulatory decision-making for future minewater energy developments across the UK.

Beyond the technical achievements, the Gateshead project provides valuable social and economic benefits. It addresses fuel poverty by providing lower-cost heating to social housing and public services while supporting the local green economy through skills development and innovation. As a result, it stands as a flagship example of how legacy coalfield infrastructure can be reimagined to support a low-carbon future.

Deep Heat Case Study: Southampton District Energy Scheme—the UK's First Geothermal District Heating Network

The Southampton District Energy Scheme (SDES), launched in 1986, is the UK's first and longest-running geothermal district heating network. Initially catalysed by a deep geothermal exploration programme in the early 1980s, the scheme has since evolved into a multi-source, low-carbon energy network supplying heat, cooling, and electricity across the city. It is widely recognised as a flagship example of sustainable urban energy integration, demonstrating the potential for deep geothermal resources in the Wessex Basin aquifer and their role in the UK's heat decarbonisation strategy.[142]

Origins and Development

In the early 1980s, the Southampton City Council (SCC), with support from central government and the European Union, investigated the deep Triassic sandstone aquifers beneath the city. Drilling in 1981 and 1982 reached 1.7 kilometres depth, accessing a geothermal resource of approximately 74°C hot saline water from the Wessex Basin aquifer. Despite scepticism from some geologists at the time—many predicted the well would "die by the mid-1990s"—the geothermal source remains operational almost four decades later, providing around 15% of the SDES total annual heat supply.[143]

The SCC recognised the opportunity to combine this renewable resource with a public-private partnership to deliver district energy infrastructure. Partnering with Utilicom (now part of Equans/Bring Energy), the Southampton Geothermal Heating Company was established to finance, develop, and operate the network.

The initial anchor customers included the civic centre and other council-owned properties, providing early revenue stability before expanding into commercial and residential markets.[144]

System Configuration and Scale

The scheme utilises a deep geothermal source from the Triassic Sherwood Sandstone aquifer within the Wessex Basin, with 74°C saline water extracted from a depth of 1.7 kilometres via a downhole turbo-pump and transferred through heat exchangers to a clean-water distribution circuit. Geothermal energy contributes around 15% of annual demand, with the majority of heat supplied by three CHP units, including a 5.7 megawatts electric dual-fuel engine that provides more than 70% of the total annual heat load. Eight gas-fired boilers supply additional top-up and peak heat when required, while a district cooling network that

GEOLOGY OF THE GEOTHERMAL WELL

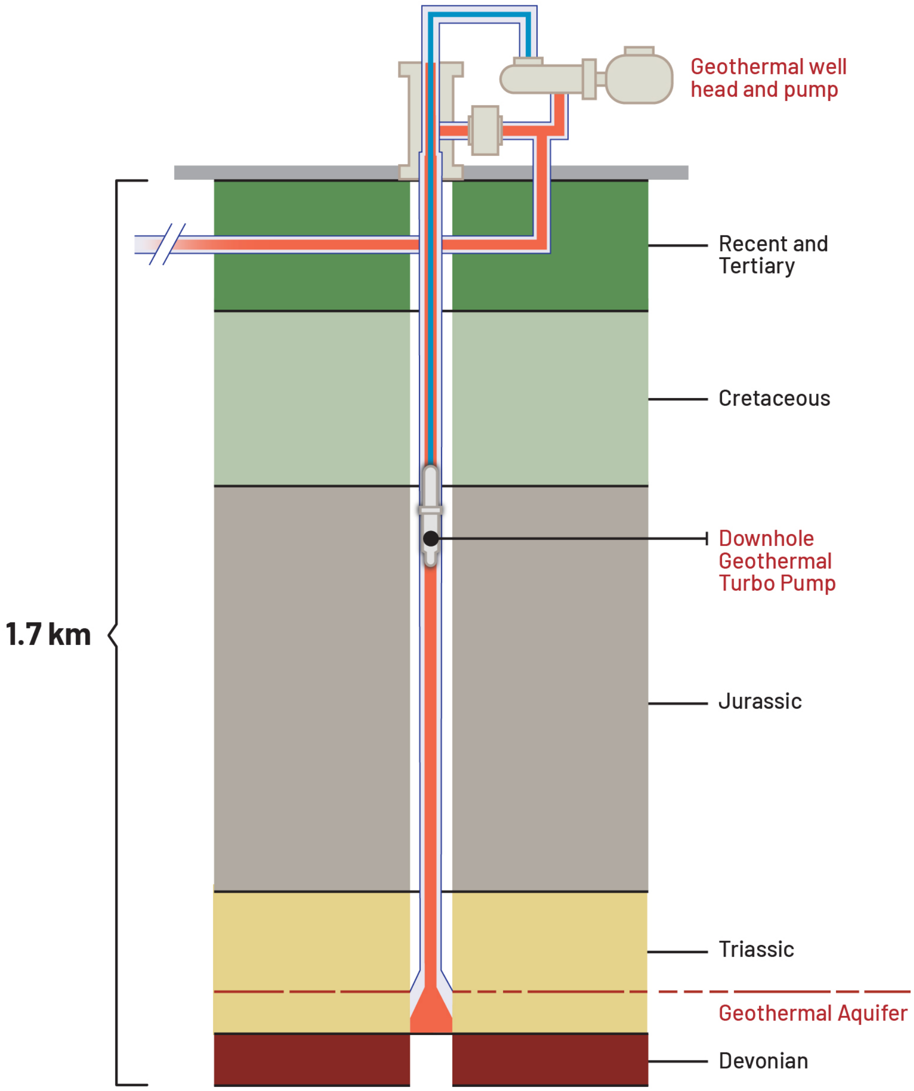

Figure 4.13: Hot water at 74°C is pumped up from a depth of 1.7 kilometres beneath the city centre. Utilising heat exchangers, it is used to heat water for the scheme. At present, 15% of the energy used by the scheme is provided by the geothermal heat source. Source: Southampton City Council & Utilicom. (2003). *Urban community heating and cooling: The Southampton District Energy Scheme*. Southampton Geothermal Heating Company.

has been operational since 1994 uses both absorption chillers powered by surplus CHP heat and conventional vapour-compression chillers.[145]

The network consists of more than 11 kilometres of insulated distribution pipes, delivering approximately 70 gigawatts thermal and cooling annually alongside 23 gigawatts thermal of exported electricity under long-term contracts.[146] It serves more than 45 major customers and hundreds of households, including BBC South Studios, the Royal South Hampshire Hospital, the University of Southampton, Westquay Shopping Centre, and multiple hotels.[147] In 2023, SDES supplied more than 40 gigawatts thermal per year of low-carbon heat and chilled water to the city centre, with the geothermal source continuing to provide a reliable baseload despite the increased contribution from CHP.

The scheme delivers significant carbon savings, avoiding an estimated approximately 11,000 tonnes of CO_2 annually compared with conventional gas boilers. Future decarbonisation strategies include phasing out gas-fired CHP, expanding large-scale heat pump integration, recovering additional waste heat, and enhancing geothermal capacity. System reliability is underpinned by the network's statutory utility status, ensuring coordinated protection of buried infrastructure, alongside built-in redundancy through dual-fuel CHP units, standby boiler capacity, and minimal network heat losses of approximately 1°C per kilometre. Reflecting its long-term success and strategic role, the 2025 *Southampton Heat Network Zoning: Zone Opportunity Report* identifies Southampton as one of the UK's leading heat network growth zones, positioning SDES as a cornerstone for future low-carbon urban heating and cooling infrastructure.[148]

Summary

The success of the SDES has been driven by a durable governance model and a strong public–private partnership between the SCC and Utilicom/Bring Energy. Underpinned by long-term customer contracts (typically 20 years), the scheme ensures both price competitiveness and investment security, while planning policy alignment—including the use of Section 106 agreements[149]—has enabled the SCC to encourage or require new developments to connect to the network. The project has received national recognition, including the Queen's Award for Enterprise (2001) and the Community Heating Award (1999), underscoring its role as a flagship low-carbon infrastructure project in the UK.

For policymakers and investors, SDES provides clear lessons. It demonstrates the proven viability of deep geothermal integration in urban UK settings, with nearly 40 years of continuous operation despite early scepticism about resource longevity. By integrating multiple heat sources—including geothermal, CHP, and waste heat, with future plans for large-scale heat pumps—the scheme delivers operational flexibility and resilience, while supportive planning and zoning policies have de-risked investment and created a bankable framework. Looking ahead, Southampton is strategically positioned to decarbonise CHP, expand geothermal production, and integrate additional renewable sources, cementing its role as a national hub for low-carbon heat innovation.

With its mature technical design, stable governance, and scalable delivery model, SDES offers a replicable pathway for deploying large-scale, low-carbon district heat networks across the UK—from high-potential areas such as southern England (Wessex Basin), which shows the highest heat-in-place values suitable for direct-use heating and potential low-enthalpy power generation, to smaller but significant hot spots in north-west England (Cheshire Basin) and distinct demonstration opportunities in Northern Ireland (Larne and Lough Neagh basins). (See Chapter 3, Figure 3.7, as reference.)

GEOLOGICAL COOLING AND STORAGE FOR THE UK'S AI GROWTH ZONES

The rapid growth of the UK's artificial intelligence (AI) and data centre sector is driving unprecedented demand for cooling, with associated electricity use and carbon intensity rising sharply. Cooling alone already accounts for roughly 40% of total data centre electricity consumption,[150] and as AI workloads push rack power densities from traditional 5 kilowatts to 10 kilowatts toward 30 kilowatts or more, these systems are generating far greater heat per square metre,[151] which is expected to significantly increase the sector's cooling energy needs. Market forecasts suggest that demand for data centre cooling infrastructure in the UK could grow by more than 20% in the coming years, reflecting both rising computational intensity and the expansion of new AI-dedicated facilities.[152] Without corresponding improvements in efficiency or waste heat recovery, cooling is poised to remain one of the largest contributors to the sector's total power draw and emissions.

Many of the UK government's proposed AI Growth Zones[153] (AIGZs)—including Culham, Thames Valley, Bristol, Teesside, Humber, and the Scottish Green Freeports—sit near thick sedimentary basins and within or adjacent to legacy onshore mining districts. Together, these settings offer some of the country's strongest opportunities for geothermal and subsurface cooling and storage resources.

Sedimentary aquifers provide stable temperatures for groundwater-based cooling and storage, circulating water between cold and warm wells to deliver low-carbon cooling and store recoverable waste heat. In parallel, flooded mine workings beneath many industrial corridors (such as the Central Belt of Scotland, Northern England, South Wales, and the Midlands) provide extensive, well-connected subsurface reservoirs with high flow potential, enabling district-scale thermal networks. For large computing hubs and AI campuses where cooling can approach 40% of total energy demand, the subsurface (aquifers and mines) offers a direct path to energy efficiency and carbon reduction.

Analysis of geological and infrastructure data sets (see **Figure 4.14**) shows that the majority of current and planned AIGZs[154] are underlain by thick sedimentary successions and/or mapped minefields, creating multiple technical options (for example, ATES, open-loop groundwater, and minewater systems). Notably, the first two confirmed AIGZs align with basins where geothermal cooling could be deployed to reduce costs and peak power demand. In particular, Culham (Oxfordshire) and Teesside (north-east England)—the first two confirmed AIGZs—both coincide with the sedimentary basins where geothermal cooling could be deployed and help reduce costs and energy demand.

1. **Culham, Oxfordshire:** The UK's first confirmed AIGZ, located near the UK Atomic Energy Authority and earmarked for fusion-powered energy systems. Culham lies within the Wessex–Worcester Basin, where the Sherwood Sandstone Group provides a permeable aquifer network suitable for ATES and shallow geothermal cooling.
2. **Teesside (North East England):** The second designated AIGZ, centred around the Teesworks site, a former steelworks undergoing large-scale regeneration. Plans include one of Europe's largest data-centre campuses (≈500,000 square metres). Centred on the Teesworks regeneration area above the East Yorkshire–Lincolnshire Basin and adjacent to the former Durham/Northumberland coalfield, this pairing of sedimentary aquifers and mine networks is well suited to hybrid systems that combine aquifer cooling with minewater heat rejection and storage for a planned large data-centre campus.

Geothermal Data Centre Cooling Is Already Happening Around the World

The Iron Mountain Data Centers in Boyers, Pennsylvania, in the United States, uses a unique geothermal cooling system located around 61 metres underground in a former limestone mine. The system uses an underground reservoir for cooling, and its mechanics are not overly complex, which keeps maintenance costs low. The data centre also has unlimited backup thermal storage capacity, unlike standard diesel backup generators, which can only provide energy for a limited number of hours. With this system, Iron Mountain saw a 34% reduction in total energy use.[155]

Beyond the confirmed sites at Culham and Teesside, more than 200 regions across the UK have expressed interest in hosting AIGZs. Many of these candidate locations coincide with major sedimentary basins and onshore mines, creating strong opportunities for renewables-integrated sedimentary storage and cooling systems supporting AI and digital campuses:

1. **Scotland (Forth, Cromarty, Irvine, Glasgow):** Coastal and nearshore basins (Forth and Moray Firth groups) contain thick sandstones. Legacy mines include the Central Belt coalfields (such as

POTENTIAL AREAS FOR DATA CENTRE COOLING AND/OR STORAGE

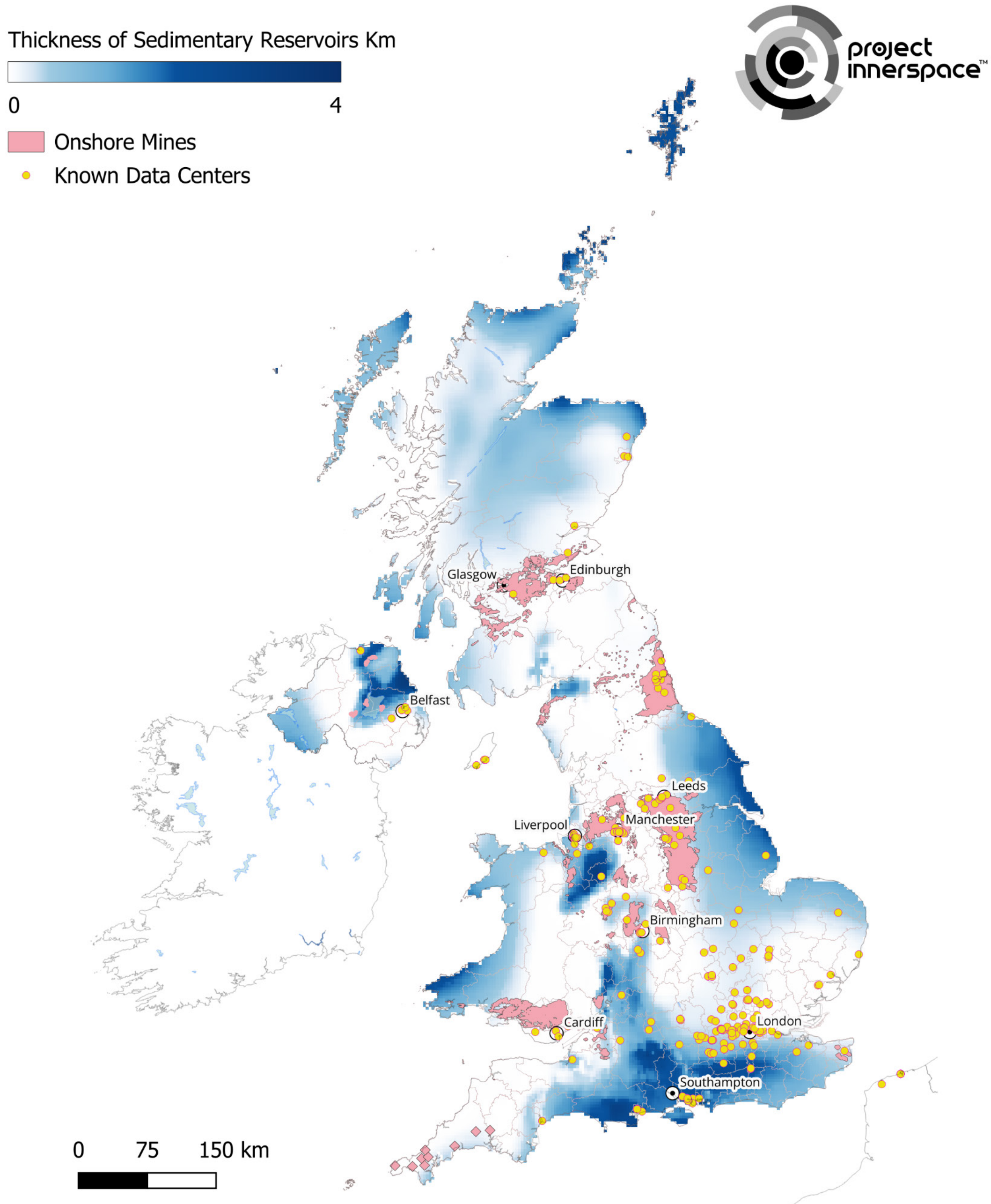

Figure 4.14: Thickness of sedimentary reservoirs across the UK (darker blue = thicker, km), with known data centres (yellow points) and onshore mines (pink areas). Thick basin sequences (for example, Cheshire, Wessex, Worcester, and East Yorkshire-Lincolnshire, plus the Larne and Lough Neagh basins) coincide with clusters of data centres, while extensive onshore mining districts (Central Belt of Scotland, Northern England, South Wales, the Midlands) add minewater geothermal opportunities. The overlap of thick aquifers, legacy mines, and digital infrastructure highlights priority zones for low-carbon cooling, thermal storage, and geothermal-ready AI growth zones. Projection: OSGB36/British National Grid. Map created by Project InnerSpace. Data sources: Holdt, S., Slay, R. & White, N. (2025). *Global sediment thickness* (in preparation). Project InnerSpace; ArcGIS Hub. (2025). Mineral mines. *UNESCO WHC sites dossiers elements core points*; Fleiter, T., Manz, P., Neuwirth, M., Mildner, F., Persson, U., Kermeli, K., Crijns-Graus, W., & Rutten, C. (2020). *Documentation on excess heat potentials of industrial sites including open data file with selected potentials* (Version 2). Zenodo; British Geological Survey. (2020). *Coal resources for new technologies dataset*; British Geological Survey. (n.d.). *BGS Geology 625K*; Abesser, C., Gonzalez Quiros, A., & Boddy, J. (2023). *Evidence report supporting the deep geothermal energy white paper:* The case for deep geothermal energy—unlocking investment at scale in the UK. British Geological Survey.

Glasgow/Clyde Gateway, Ayrshire, Fife), offering extensive flooded workings suitable for mine-cooled systems.

2. **North-West England (Manchester–Liverpool–Warrington corridor):** Within or adjacent to the Cheshire Basin, with extensive Sherwood Sandstone aquifers. Nearby legacy mines include the Lancashire coalfield, North Staffordshire (Potteries), and Cheshire salt mines (for example, Winsford), all providing large subsurface void space and warm water.
3. **Yorkshire and the Humber (Doncaster, Drax, University of York):** Over the East Yorkshire–Lincolnshire Basin with thick Mesozoic strata. Major legacy workings include the Yorkshire coalfield (Selby complex/Kellingley, Hatfield, Barnsley–Rotherham–Doncaster belt), well suited to minewater networks alongside aquifer systems.
4. **North Lincolnshire:** Underlain by Permo-Triassic and Jurassic sequences. Proximal legacy mines include the Humberhead Levels/South Yorkshire coalfield fringe and Gainsborough–Doncaster area collieries; several sites retain accessible shafts and flooded workings.

Co-locating data infrastructure with renewable and geothermal energy would also help deliver the UK's sustainable and energy-resilience objectives while positioning the country as a global leader in sustainable digital infrastructure.

CONCLUSIONS

- **Shallow geothermal systems:** Currently the most mature and widely deployed opportunity, with around 43,700 GSHP installations nationwide. These systems are readily scalable and increasingly integrated into fifth-generation low-temperature heat networks.
- **Aquifer thermal energy storage:** Represents a major opportunity for urban heat and cooling decarbonisation. National modelling suggests ATES could theoretically supply up to 61% of annual heating demand and 79% of cooling demand, but UK deployment remains limited (11 installations) compared with leading international examples. The Chalk and Triassic Sherwood Sandstone Group aquifers—which combine favourable hydraulic properties with proximity to major urban centres (including London, Southampton, Cheshire, and Manchester)—are well suited for integration into district heating and cooling networks and should be considered priorities for ATES development.
- **Minewater geothermal:** Offers an immediately deployable, low-risk pathway by repurposing the UK's approximately 23,000 abandoned mines and 2 billion cubic metres of flooded workings as shallow, low-cost heat sources. The 6 megawatt Gateshead scheme, commissioned in 2023, demonstrates this potential. Ongoing projects across former coalfield regions—including in the north-east, Yorkshire, South Wales, and the Midlands—are also working on feasibility studies and pilot possibilities.
- **Cooling:** Many of the UK government's proposed AIGZs—including Culham, Thames Valley, Bristol, Teesside, Humber, and the Scottish Green Freeports—sit near thick sedimentary basins and within or adjacent to legacy onshore mining districts. Together, these settings offer some of the country's strongest opportunities for geothermal and subsurface cooling and storage resources.

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