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Geothermal energy

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Summary

Geothermal energy is not recognised by law as a natural resource in the UK (like water or gas), and there is currently no bespoke regulatory system for the licensing, ownership and management of the geothermal resource.

Geothermal energy is the heat generated and stored in the ground and is a source of low-carbon, renewable energy. It is homegrown, available throughout the UK at depths from a few metres to several kilometres and can provide heat or power all year long. It is not dependent on weather conditions and can deliver baseload energy for balancing more intermittent power generation from renewable sources like solar or wind.

Geothermal technologies currently deliver less than 0.3% of the UK's annual heat demand, using only a fraction of the estimated available geothermal heat resource. There is the potential to increase this proportion significantly and contribute to the UK's net zero targets. However, a lack of information about the application of the technology in the UK has meant that deep geothermal is not currently factored into the UK's carbon budget or government strategies. Roll-out may require long-term government support to develop demonstration projects and expand the industry.

Geothermal resources are broadly grouped into shallow and deep geothermal, based on the system temperatures and the technologies used for extracting the heat. Shallow systems generally require ground source heat pumps to modify the temperature obtained from the geothermal resource for use in domestic or commercial heating or cooling applications. In deep systems, the resource is at a high enough temperature to be used directly for heating or electricity generation.

The potential of geothermal energy in the UK has been investigated at various times since the 1970s when a review of geothermal resources was undertaken as part of the Geothermal Energy Programme funded by the UK Government and the European Commission. Although it identified geothermal resources across all parts of the country, the UK's current usage is lower than that of other European countries that have similar resources.

In countries like Germany and France, geothermal energy has been shown to offer environmental, economic and technical advantages in comparison to other renewable and non-renewable heating sources. These include a small land area footprint, applications over a range of scales from individual homes to district heating scale, very low greenhouse gas emissions, and the long-term availability of the resource. Paris, for example, has been using geothermal energy for heating since 1969, today supplying geothermal heat to 250,000 households via 50 heating networks.

Geothermal energy is not recognised by law as a natural resource in the UK (like water or gas), and there is currently no bespoke regulatory system for the licensing, ownership and management of the geothermal resource. Activities are controlled under existing regulations developed for petroleum exploration or water resource use and protection. At current levels of deployment, this approach is generally regarded by regulators and industry as being adequate for managing potential environmental and operational impacts. However, some industry stakeholders regard certain aspects of this

There is consensus among geothermal stakeholder groups that a 'route to market' is needed for the geothermal sector to develop in the UK.

repurposed regulatory system as being over-engineered for regulating deep geothermal energy in the UK. In addition, the multi-agency set-up for deep geothermal is seen as a barrier to deployment by some as it makes the approval process complicated and time consuming. Some shallow geothermal systems are not currently regulated, but it is acknowledged by the regulator that an update of existing regulations may be required when environmental impacts of multiple systems, such as high-density urban deployments, are better understood.

Streamlining the regulatory process is seen by industry as an important measure to facilitate the wider uptake of geothermal technologies. This could take the route of assigning a single, bespoke geothermal regulator or an agency that coordinates the approval process.

Development and exploration of geothermal energy systems can have minor environmental impacts on subsurface temperatures and groundwater quality. They may also be associated with the emission of some greenhouse gases, indirectly through using non-renewable electricity for the operation of heat pumps or directly through releasing gases contained in deep geothermal fluids. Geothermal schemes, if not executed optimally, can also carry some drilling and operational risks, including induced seismicity although these would typically be of very low magnitude.

There is consensus among geothermal stakeholder groups that a 'route to market' is needed for the geothermal sector to develop in the UK. Building such a market framework for the different geothermal technologies could be achieved by adopting strategies similar to those provided to other renewable technologies. As evidenced by other sectors in the UK, like offshore wind, long-term government support that includes ambitious targets and subsidies could contribute to rapid cost reductions for geothermal energy systems. Stakeholders argue that the absence of long-term targets and policies that support the development of skills, supply chains and a service industry are one of the main reasons why geothermal energy in the UK has fallen behind that of other similar countries.

Upfront grants, like the new Boiler Upgrade Scheme, and subsidies like the now closed Renewable Heat Incentive are thought to be effective measures for encouraging technology adoption, but there are concerns that the current level of support and duration over which it is available is insufficient for a market to develop. While some financial support is available for geothermal power projects, there is currently no support for geothermal heating systems of more than 45 kW capacity unless developed as part of a heat network. Geothermal risk mitigation schemes are highlighted by the European Geothermal Energy Council as one of the key mechanisms for stimulating the development of deep geothermal projects, especially during stages of low market maturity. Such schemes currently do not exist in the UK.

Developing the geothermal sector could provide considerable economic stimulus and contribute to job generation, including the redeployment of both technologies and workers from the oil and gas industry who have transferable skills and experiences in risk assessment and mitigation, deep-drilling and reservoir development, and management. However, high upfront capital costs and the geological risk of not achieving the required temperatures or water flows presents a major barrier to the development of geothermal heat and power projects in the UK.

Introduction

This POSTBrief uses the following structure:

- **Part 1** provides a brief overview of the geothermal resources stored in the shallow and deep subsurface of the UK and the technologies used to extract geothermal energy from the different geothermal systems, including: the shallow ground and aquifers; abandoned mines; hot sedimentary aquifers; disused oil & gas wells; and hot crystalline rocks.

- **Part 2** describes the potential role of geothermal energy in the UK decarbonisation efforts, specifically the decarbonisation of heating, including examples of geothermal heat network developments in the UK and a case study of what has contributed to the successful development of geothermal district heating in the City of Munich.

- **Part 3** highlights the main environmental impacts and risks that can be associated with geothermal energy, including: subsurface temperature changes; impact on groundwater resources; emissions and microbial risks; and drilling and operational risks.

- **Part 4** outlines the opportunities and barriers for developing a geothermal market in the UK, looking at: policy mechanisms that could support a route to market; opportunities and barriers for integrating geothermal sources in local and regional heat planning; technology awareness; and public acceptance and consumer experiences linked to geothermal technologies in the UK.

- **Part 5** describes the policy and regulatory frameworks that are applicable to geothermal energy developments in the UK and the devolved nations. Following an overview of the available government support for geothermal energy, this section analyses the regulatory process, including: licensing and permitting; governance of the heat resource; land access rights; and induced seismicity regulations.

- **Part 6** concludes with an outlook of future developments and innovations that could advance geothermal energy use in the UK and worldwide.

What is geothermal energy?

Geothermal energy is the energy generated and stored in the form of heat in the rocks and soils beneath the surface of the solid Earth.

Geothermal energy is the energy generated and stored in the form of heat in the rocks and soils beneath the surface of the solid Earth (Figure 1).[1] This heat originates from two principal sources: heat generated by the decay of the long-lived radioactive isotopes of uranium, thorium and potassium in the Earth's crust and mantle,[2,3] as well as from residual heat released during the Earth's formation.[4,5] Heat moves from within the Earth to the surface and gives rise to an increase in temperature with increase in depth - the geothermal gradient. This varies across the globe and in the UK is around 27°C/km, but locally it can exceed 35°C/km.[6] Subsurface temperatures at 1,000 m, 3,000 m and 5,000 m are consequently around 40°C, 90°C and 150°C, respectively.

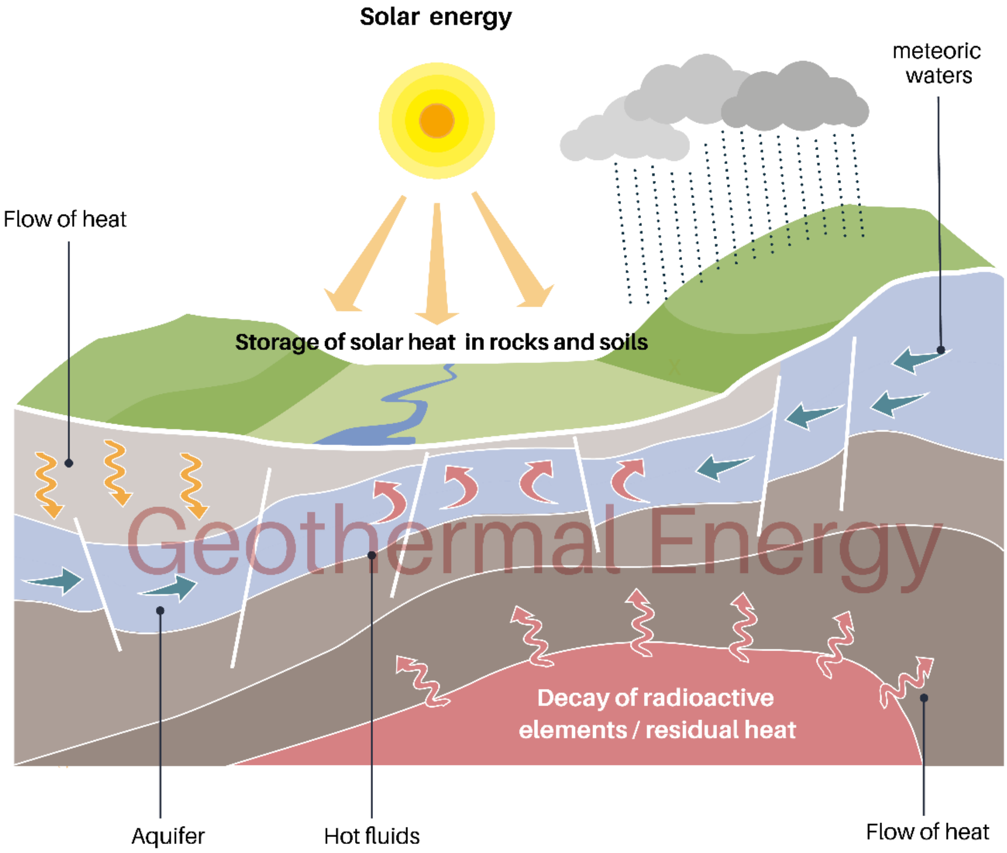

Figure 1: Origins and flows of geothermal energy in the Earth (© UKRI 2022)

The total thermal energy of the Earth is huge (12.6 x 10^{24} megajoules),[7] but only a fraction of it can be used. Most use is limited to areas where favourable geological conditions permit a carrier (such as water in liquid or vapour phase) to transfer the heat from deep hot zones to the surface. Traditionally, high temperature power generation systems of above 200°C are usually only found at the margins of tectonic plates.

Energy from the sun that is stored in rocks and soils in the form of heat is also a form of geothermal energy[1] and constitutes a useable renewable resource. Although the estimated energy flows at the Earth's surface are much larger (1–2 watts per square metre)[8] compared with those from sources within the Earth (around 0.052 watts per square metre for most of the UK),[6] the dominating heat transfer process (conduction) limits the depths to which the heat can penetrate into the ground. The heat is typically stored in the upper 10–15 m of the ground and is distributed via meteoric water, through permeable rocks that transmit groundwater (aquifers, see definitions in the glossary and POSTbrief 40), and through human-made underground structures, such as flooded mines.

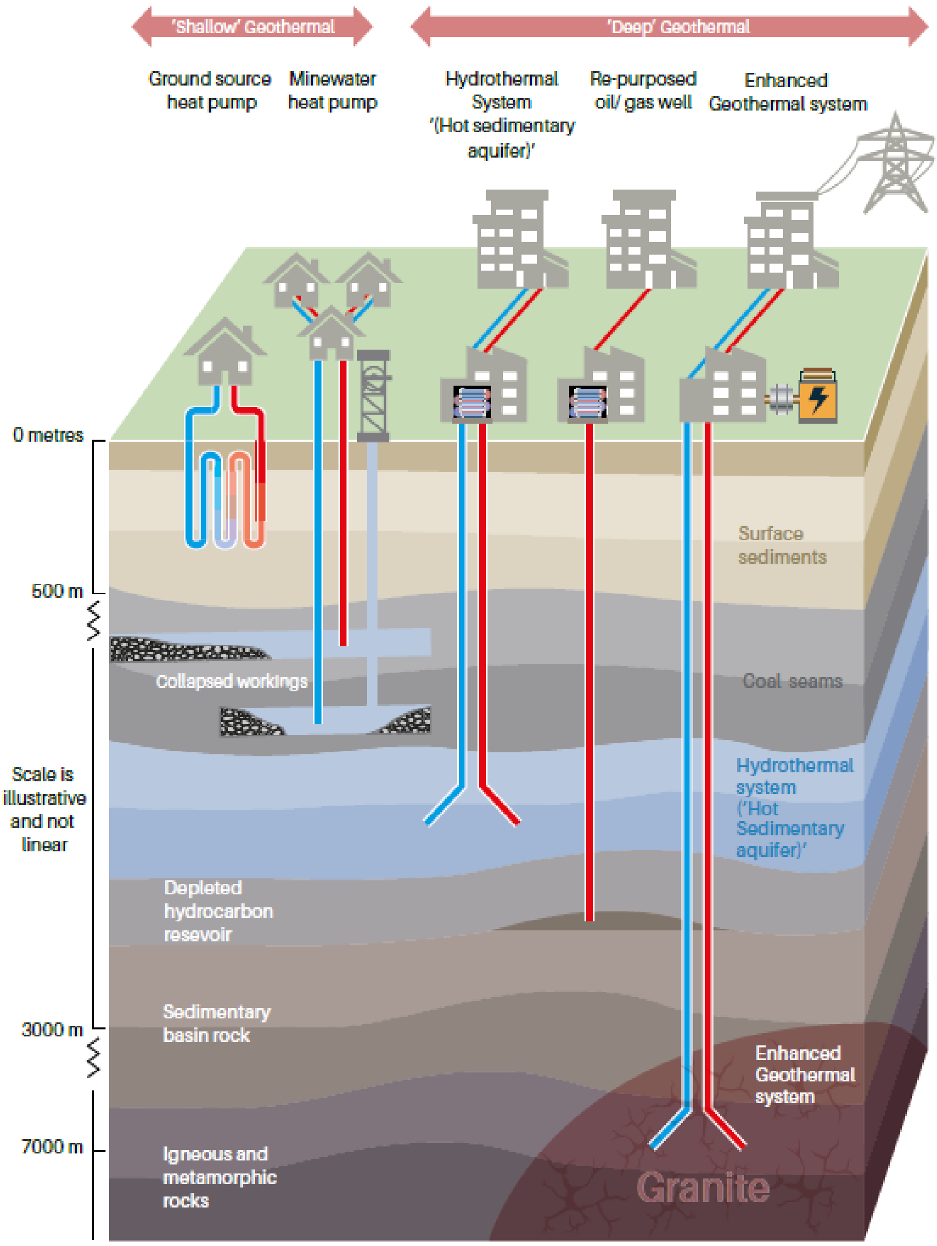

Figure 2: Geothermal technologies applicable in the UK (after Townsend et al 2020[9])

Beneath urban areas, the natural subsurface heat resource is often enhanced by heat losses from building basements and subsurface infrastructures.[10] Raised subsurface temperatures are noted beneath many urban areas in the UK[11–13] and worldwide[14–17] – a phenomenon termed subsurface urban heat island (SUHI).[18] Despite the modest increases in temperature (2–5°C),[11,19] research suggests that the SUHI constitutes a considerable human-made geothermal heat resource in the UK (for example in Cardiff[20]) and many cities around the world.[19,21]

Geothermal energy can be used to produce constant electrical or thermal energy throughout the year irrespective of the weather conditions.

Geothermal energy can be used to produce constant electrical or thermal energy throughout the year irrespective of the weather conditions.[22] Depending on the prevailing temperatures, pressures and geological conditions, geothermal energy is exploited by different technologies for a range of uses. At the broadest level, systems are classified according to the type of the heat source (magmatic/amagmatic) and the heat transfer mechanism (conduction/convection).[23] A more informal classification for geothermal energy distinguishes between 'shallow' and 'deep' systems, but there are no clear definitions of these terms. Definitions vary within UK legislation. For example, the Infrastructure Act 2015[24] defines 'deep geothermal' as more than 300 m below the surface whereas the Renewable Heat Incentive (RHI) Scheme Regulation 2018[25] defines it as more than 500 m.

Due to the lack of clear definitions, the terms deep and shallow are often used very loosely to group together different geothermal technologies. In this briefing paper, the terms will used as described below, and Figure 2 gives a summary of the various types of geothermal systems that are discussed in more detail in Chapter 3.

- **Shallow geothermal systems**
  Systems that capture the low temperature heat resource (typically temperatures of 10–25°C) stored in the shallow ground, groundwater and flooded mines. They require ground source heat pumps (GSHPs) (PN 426) to transfer the heat for use in space and water heating or cooling for individual buildings or multiple properties supplied by a heat network. GSHPs are a mature technology that can be fitted to new and existing buildings and are deployable in nearly all geological settings. Depending on system type and size, they may require a substantial amount of subsurface space for the installation of the ground infrastructure, which can constrain their deployment in build-up areas, especially when retrofitting systems to existing buildings in dense urban settings.

  As ground temperatures are generally more stable and higher than air temperatures during winter months when most heat is needed, GSHP systems are typically more efficient than air source heat pump (ASHP) equivalents and have lower running costs. However, despite being a mature technology, upfront costs for (domestic) GSHPs are generally higher than for an equivalently sized ASHP. In addition, their installation can be more disruptive because of the requirement to install ground infrastructure. While offering a widely deployable solution for new builds, retrofitting GSHPs can be expensive and may require upgrades to home insulation and heating systems.

- **Deep geothermal systems**
  Systems that require the drilling of deep wells to reach higher temperature heat resources (typically 50–200°C in the UK). This heat can be used directly (without the use of a heat pump) in district heat networks for domestic or commercial space heating, industrial process heat or, in some areas of the UK, for power generation. Although the theoretical geothermal energy resource is enormous, current high costs of drilling restrict the economically viable exploitation of geothermal energy to areas with specific geological settings (Figure 8). As technologies improve and new extraction methods develop, more of the currently inaccessible resource will become available.

1 UK geothermal resources and technologies

This chapter describes the various technologies that are used to extract geothermal energy from the ground and convert it into usable heat or electrical energy for consumers. The potential location and scale of the relevant geothermal resource in the UK is also discussed.

1.1 Shallow geothermal energy

The low-temperature heat resource (10–25˚C) that is stored in the shallow subsurface (tens of metres to around 500 m beneath the surface) is typically exploited through ground source heat pump (GSHP) systems. The availability of different systems in which heat is stored (the ground, aquifers, mine water systems – see Figures 4 and 5) together with the different types of GSHPs (closed-loop; open-loop – see Figure 4) coupled with flexible design options mean that deployment of these shallow geothermal systems is feasible almost anywhere in the UK (Figure 3).

According to the International Energy Agency (IEA) Geothermal Annual report 2022,[26] the UK has an estimated 43,700 installed GSHP systems, compared to more than 440,000 and 210,000 installed systems in Germany (in 2020)[27] and France (in 2018),[28] respectively. Together with operational deep geothermal direct-use and mine geothermal schemes in the UK, they generate around 1,330 GWh per year.[26] This means that currently only 0.3% of the UK's annual heat demand is supplied by geothermal sources.

GSHPs extract heat or cold from the ground either via a 'closed-loop' borehole heat exchanger (BHE) in which a heat carrier fluid is circulated through pipes installed in the ground (Figure 4b), or via an 'open-loop' system where groundwater is pumped directly from aquifers or flooded mines (Figure 4a and 5, respectively).[29] Open-loop systems typically operate as 'doublet' systems that require the drilling of two boreholes – one for abstracting water and one for returning (cooled/warmed) water to the aquifer. There are also single borehole open-loop systems, so called 'standing column' wells, that abstract from and return water to the same borehole. A few of these systems are in operation in the London chalk aquifer. The heat pump (PN 426) moves the heat from the fluid to the building's heating systems, using a compressor to increase the temperatures (to more than 40°C) for use in space or hot water heating. The carrier fluid or groundwater is usually returned to the subsurface, but some open-loop systems discharge to nearby waterways (for example, the system used for cooling Portcullis House).

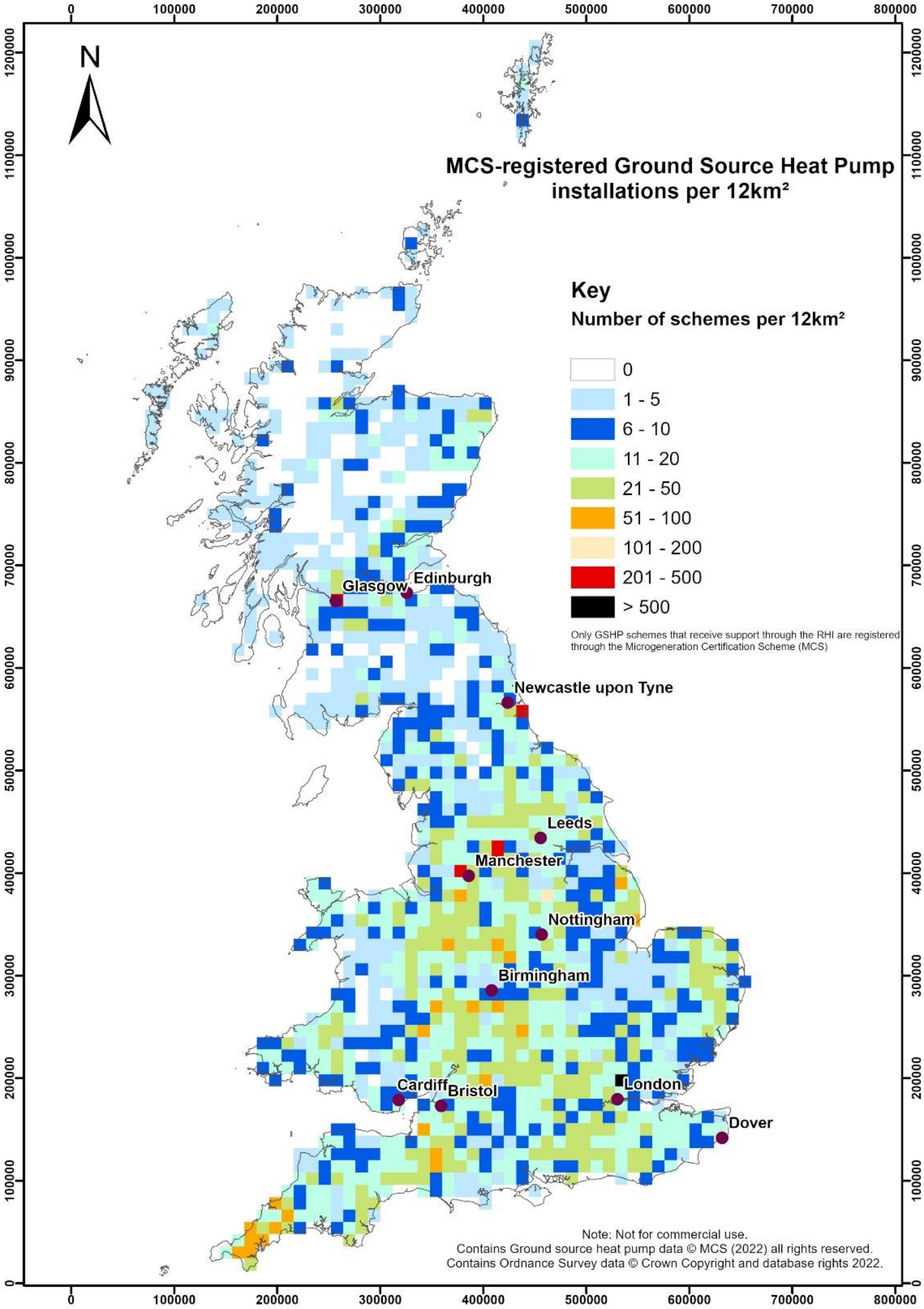

Figure 3: Numbers of ground source heat pump installations (per 12x12 km square) registered by the Microgeneration Certification Scheme as part of the application procedure for the Renewable Heat Incentive across the UK (Data source © MCS, 2022 reproduced with permission)

Electrical energy is needed to drive the heat pump, but the process is more efficient than the combustion of gas. On average, one unit of energy input to the heat pump generates 3–4 units of heat output. This gives heat pumps operational efficiencies of 300–400%, compared with an average 85% for condensing boilers.[30] However, field trials undertaken between 2008–13 have reported a notable performance gap for some heat pump installations across the UK that was attributed to poor design, commissioning and installation.[55]

Since then, the Microgeneration Certification Scheme (MCS),[31,32] a government endorsed scheme that assesses and certifies microgeneration installations and installers for low-carbon generation of electricity and heat (including heat pumps, solar thermal and biomass) has released new installation guidelines.[33] As with other new low-carbon technologies, compliance with these updated guidelines was shown to improve GSHP system performance.[34] The Department for Business, Energy and Industrial Strategy (BEIS) funded Electrification of Heat Demonstration Project (Box 4) is currently testing the performance of heat pumps in different types of homes.[35] Early results indicate that heat pumps are suitable for all UK housing types.[36]

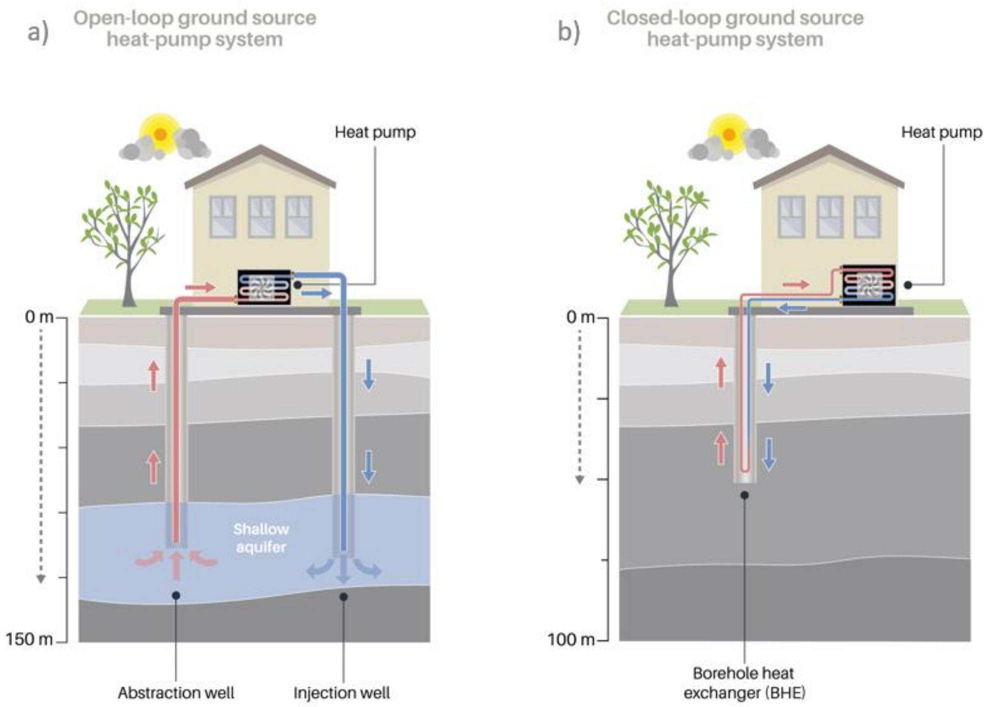

Figure 4: Different types of ground source heat pump systems (© UKRI 2022)

GSHP systems are scalable from individual buildings[37] to district-scale applications.[38,39] Scaling up requires the extraction of a greater amount of heat, for instance, by using abandoned mine water as a heat source (Section 1.2) or ambient ground-loop heat networks (also called shared ground-loops)[40] that can supply heat to more than one property. GSHPs can be used for heating, cooling (PN 642), or both heating and cooling. They can provide a synergy between decarbonisation of heat and delivering low-carbon space cooling. Demand for space cooling is forecast to rise, including in the UK.[41] If used for both, the system effectively uses the ground for inter-seasonal thermal storage of their waste heat and cold (Box 1). Natural underground temperatures are relatively stable throughout the year - warmer than the air temperatures in winter and colder than the air temperatures in summer. This temperature offset and the ability of storing and reusing thermal energy (heat or cold) from the ground make GSHPs more efficient than air source heat pumps (ASHP), resulting in additional carbon emission savings of 1–1.5 tonnes of CO_2 per year for an average (single home) domestic heating scheme.[42] For comparison, the UK's average CO_2 footprint per person is around 6 tonnes of CO_2 per year (excluding import/export, shipping and aviation).[43] In addition, GSHP-driven ambient heat and cooling networks (PN 632) experience lower system losses than high temperature networks as the temperature difference between network and ambient temperatures is very low.[40]

Box 1: Underground thermal energy storage (UTES)

In addition to space heating/cooling applications, the ground can also be used for storing excess heat from other sources, including renewables (like solar thermal) or industry. Systems that pump heat into the subsurface for storage purposes are referred to as Underground Thermal Energy Storage (UTES) systems. They can address the mismatch between heat supply and demand and increase the efficiency of renewable heating/cooling systems.[44] While UTES provides a convenient form of bulk thermal energy storage, the success of large-scale systems is largely dependent on the hydro/geological conditions as well as on a local need for district heating.[45]

UTES can be coupled to GSHP systems but can also be realised without heat pumps. There are three typical underground locations in which thermal energy is stored: boreholes, aquifers, and mines. The storage medium typically used for this method of thermal energy storage is water.

- Boreholes used for thermal storage are man-made vertical heat exchangers that circulate an energy carrier fluid through the subsurface to transfer heat between the fluid and the ground layers. These systems are referred to as borehole thermal energy storage (BTES). Storage temperatures range between 40-90°C, with storage efficiencies reported as 40-60%.[44]
- Aquifers and mines are natural storage spaces for thermal energy. Thermal energy is transferred to the aquifer or mine by the injection of hot or cold water. Storage temperatures typically range between 13–25°C (for heat storage) and 3-17°C (for cold storage), with storage efficiencies reported as 68–87%.[44] While aquifer thermal energy storage (ATES) is widely used,[46,47] mine thermal energy storage (MTES) is still at the pilot stage.[48] There is increasing interest in high temperature (more than 50°C) UTES,[49,50] but such systems are not yet deployed commercially.

1.2 Mine energy systems

The water within disused flooded mine systems can be used for geothermal heating and underground thermal energy storage. Although in most near-surface mine water systems, the temperature of the water will be at normal shallow groundwater temperatures (10–25°C),[51] the very high volumes of available water and the resultant high abstraction rates make disused mine systems ideal for large-scale open-loop GSHP systems. The system (Figure 5) is broadly the same as other open-loop shallow geothermal systems (Figure

4a) as a GSHP is still required to increase the temperature of the mine water to a useable level.

In some mine systems, pumping has caused groundwater to flow upwards from deeper, warmer horizons, resulting in elevated near surface groundwater temperatures of up to 25°C.[51] It is estimated that around a quarter of the UK's population live above abandoned coal mines (Figure 6) and that flooded shafts contain around 7,920 petajoules of heat, with the potential to store more.[52] For comparison, natural gas supplied 1,080 petajoules for domestic heating in 2020.[53] Some former colliery sites already pump large volumes of mine waters for environmental or operational reasons (for example mine water treatment).

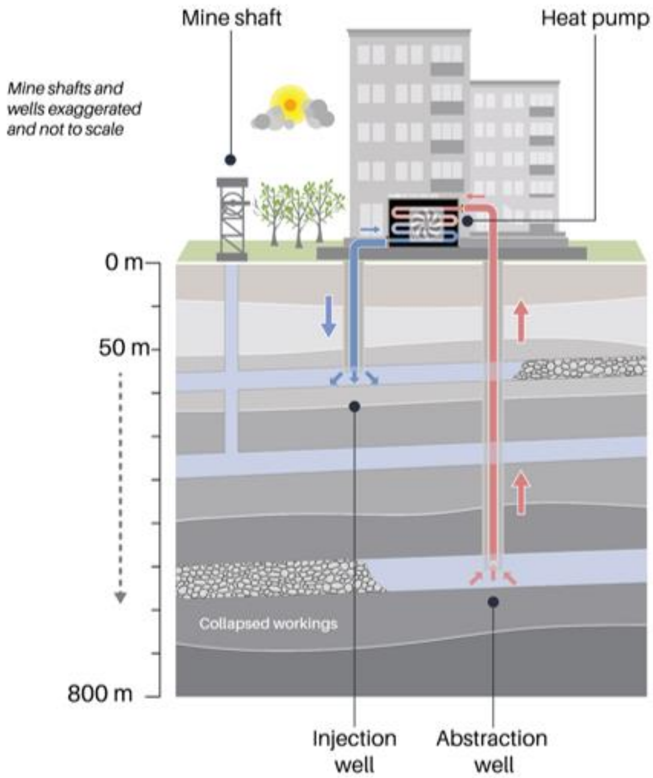

Figure 5: Mine water energy system (© UKRI 2022)

The Coal Authority, which manages abandoned coal mines in the UK, has set up small heat networks at some of these pumped sites, extracting the heat for low-carbon heating[54] of their offices and workshops.[55] There are a number of new, larger schemes currently under development (see Box 2), including some that require drilling of wells to more than 300–400 m depths within the mines.[56] The British Geological Survey has established a research site for investigating the sustainability and environmental impacts of the geothermal use of coal mines.[57] Northern Ireland has potential for extracting heat from abandoned coal mines, albeit at much smaller scales than Northern England, Wales or Scotland. While mostly located away from major urban centres, some Northern Ireland coalfields like East Tyrone are thought to merit further investigations.[58]

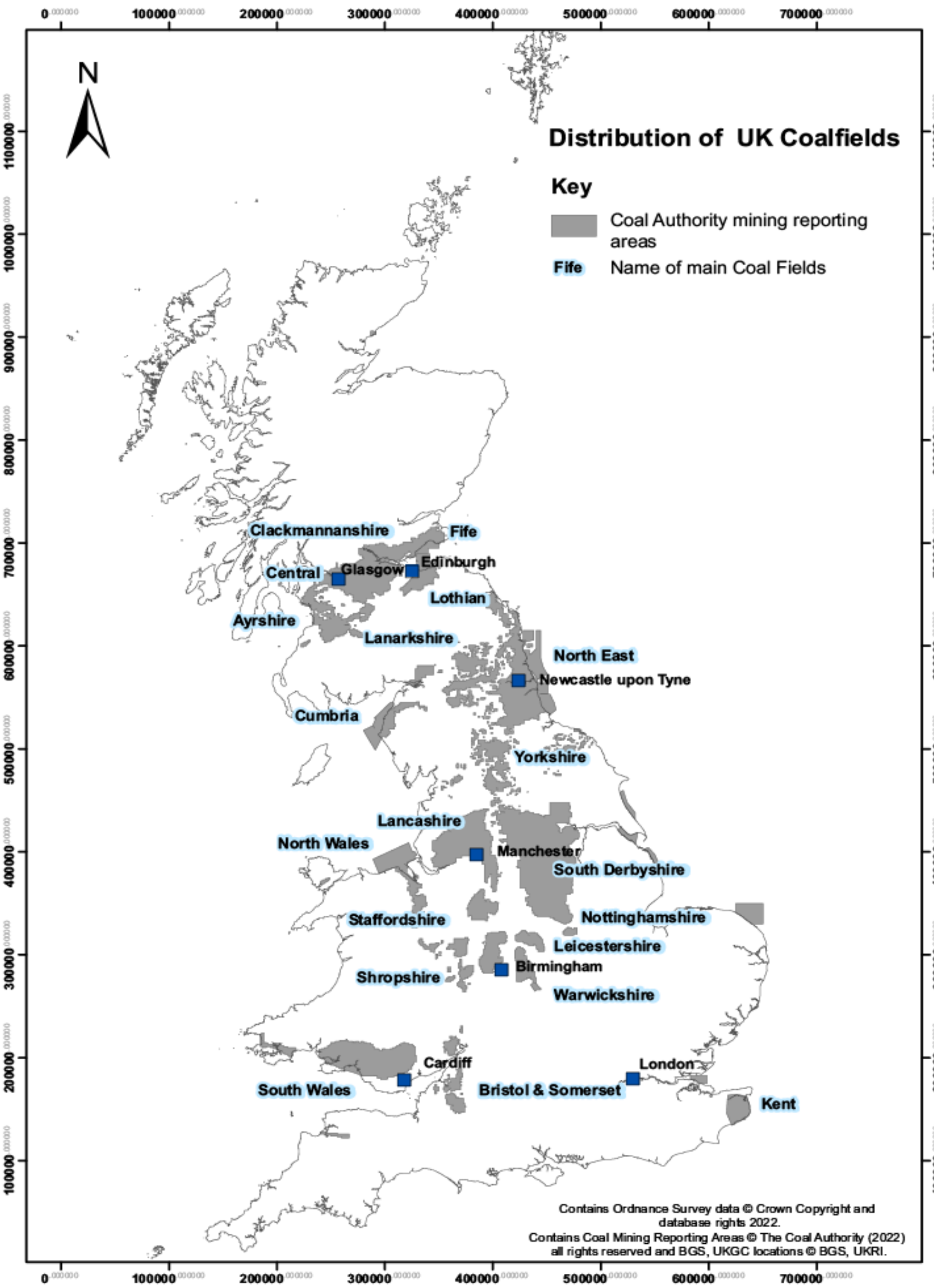

Figure 6: Distribution of GB coal fields (© UKRI 2022)

1.3 Deep geothermal systems

Most deep geothermal exploration aims to identify areas with higher temperatures nearer the surface (high geothermal gradients) where drilling is shallower and less expensive. The UK deep sedimentary basins and areas around heat-producing granites have above average geothermal gradients (such as those above 35°C/km)[6,59,60] that could potentially be exploited[61] (Figure 8). The various resources and the related technologies are described below.

Hydrothermal systems (hot sedimentary aquifers)

Sedimentary basins (deep geological basins filled with consolidated sediments) are dispersed across Great Britain (Figure 8) and parts of Northern Ireland (the Rathlin, Lough Neagh and Larne basins in the northeast and the Lough Allen and Slieve Beagh basins in the southwest[32]). Where groundwater circulation occurs within the deeply buried rocks (1–3 km), they form hydrothermal systems, also called hot sedimentary aquifers (HSAs). Hydrothermal systems arise from a combination of three geological components: fluid, heat and permeable rocks. They are considered conventional geothermal resources because they can be developed using existing technologies.[62]

The UK has a long history of using warm geothermal waters from HSAs. The thermal springs in Bath and Bristol, Derbyshire and Wales[63,64] are outflows from such deep (typically hidden) circulation systems which have been used since the 1st century for health, pilgrimage and bathing.[65,66] With temperatures of 60–80°C at a depth of more than 1.5 km, HSAs provide a potential source for direct-use heating applications (without using a heat pump – Figure 7), including district heating networks. For example, in Southampton, hot groundwater from a deep hydrothermal source provides heating to several buildings including a shopping centre, a hospital and municipal buildings (Box 2).[67] This is currently the UK's only operational direct-use geothermal scheme. In operation since the 1980s,[68,69] it has saved 131,564 tonnes of CO_2 emissions. The geothermal well was taken offline in 2020 to install a new borehole pump. The well is, presently (February 2022), not in operation due to a technical problem with another component of the district heating and cooling network unrelated to the geothermal system.[70]

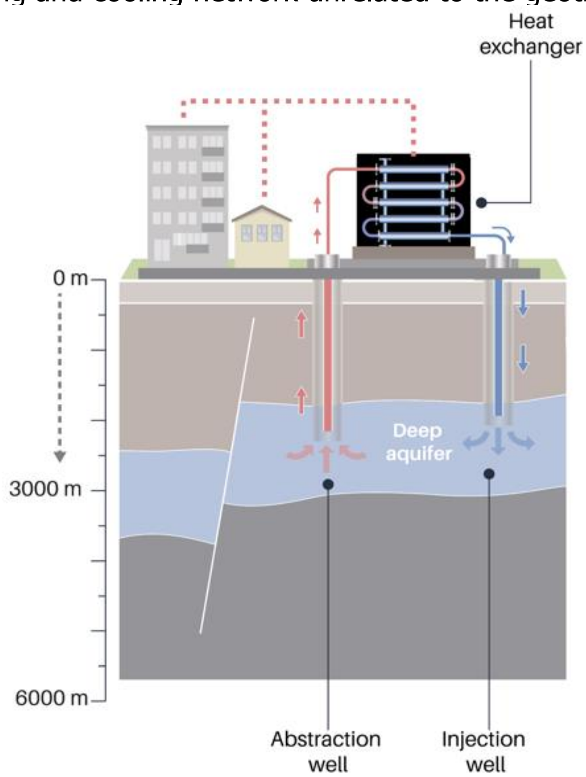

Figure 7: Geothermal doublet used to pump and reinject water from a deep hydrothermal system (© UKRI 2022)

Hydrothermal systems can occur in widely diverse geological settings but often there is no physical indicator at the surface (such as hot springs) of these deep resources. Successful exploration requires the presence of water-bearing and permeable rocks at depth, which is often difficult to predict. While various exploration techniques can reduce some of the initial uncertainty, exploration drilling to depths of around 1–3 km is normally required to confirm the resource.[71] Typically, two or more deep wells are required for a deep geothermal scheme: one for abstracting the hot water from permeable, water-filled rocks and one for re-injecting the cooled water (after heat extraction) back into the geothermal aquifer (Figure 7). This so-called geothermal doublet design is also used for exploiting enhanced geothermal systems as well as for shallow, open-loop ground source heat pumps.

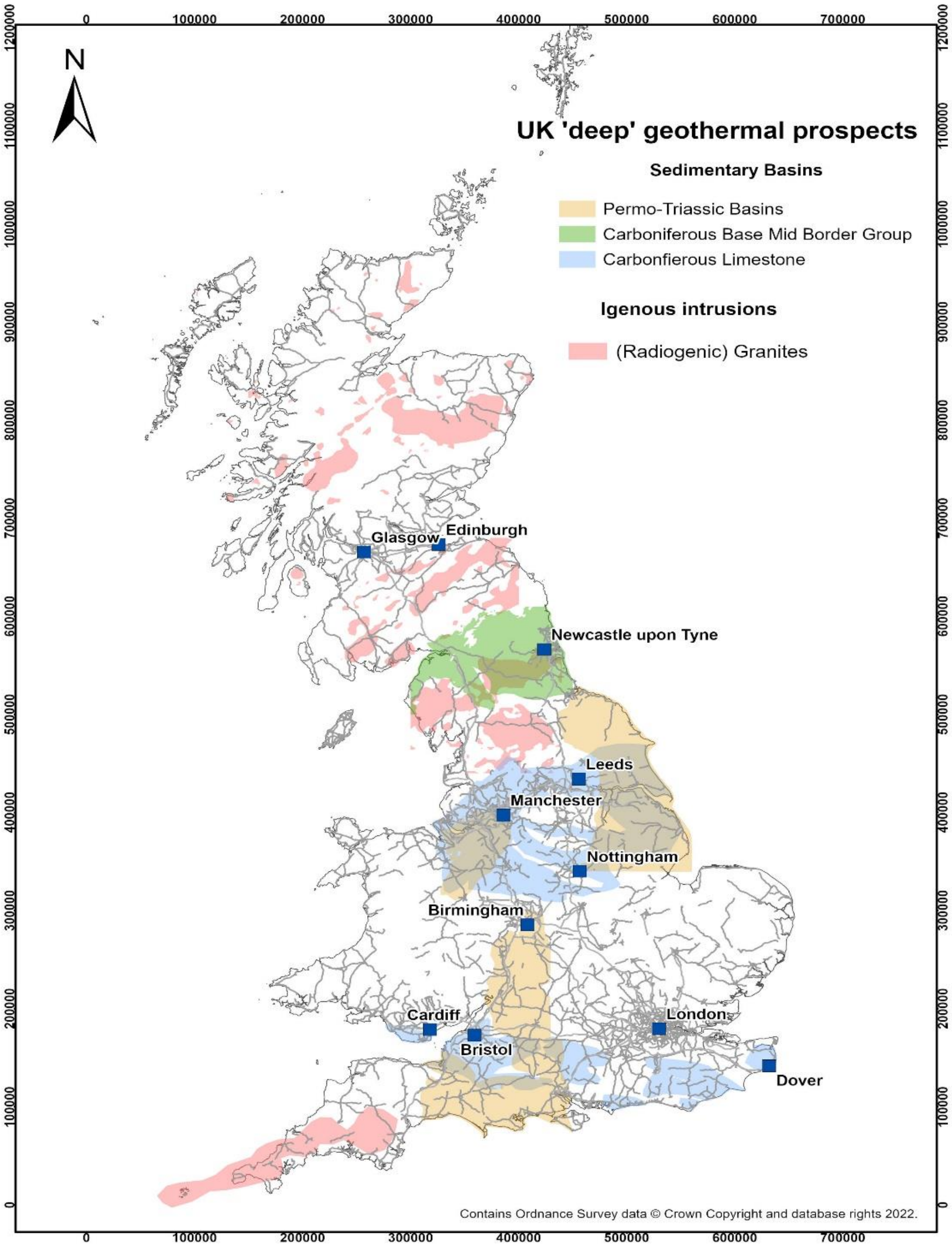

Figure 8: Distribution of GB deep geothermal targets (© UKRI 2022)

Many major population centres in the UK lie above or adjacent to sedimentary basins or HSAs. The temperatures in these basins are estimated to be in the range of 40°C to over 60°C,[6] and hence these systems are most suited to provide direct-use heating (Figure 8). The geothermal heat resource contained within these basins is estimated to be one hundred to two hundred times[6,61,72] the UK's domestic heat demand. However, as heat currently cannot be transported over long distances (because of high distribution losses along the way), opportunities for developing geothermal heat are limited to areas of high heat demand, for example for domestic heating, horticulture or industry. Where temperatures are high enough for electricity generation, geothermal energy can be fed into and distributed via the national electricity grid.

Re-purposing of disused oil and gas wells

Large volumes of hot water (brine) are a common by-product of oil and gas production from mature fields. Repurposing such wells for the production of heat[73] or electricity[74] or subsurface heat storage[75] could reduce the cost of geothermal projects by more than 40%[76] and extend the life of the field after hydrocarbon extraction ceases.

The concept of repurposing existing hydrocarbon wells has only been proven in small pilots[77] for some technologies such as doublet systems. Questions around scalability, economic performance[78] and environmental viability[79] have yet to be resolved. Generating geothermal energy from hot water co-produced during oil or gas production is being tested in the US. While it is said to deliver near-term energy savings and lower greenhouse gas emissions,[80] there is concern that geothermal/hydrocarbon co-production could prolong fossil fuel production by extending the economic life of oil and gas fields.[81,82]

Single borehole heat exchangers, also called coaxial (open-loop or closed-loop) boreholes are a new concept developed for use in single deep wells. They consist of two concentric tubes: one carrying fluid down and the other carrying fluid backup through the centre, exchanging heat during fluid counterflow (Figure 9). The technology may find specific application where a borehole already exists, for example for re-purposing conventional hydrocarbon wells or unsuccessful geothermal wells. They can also be installed in purpose-drilled wells. While less efficient than doublets, they incur considerably lower drilling costs by requiring only one borehole for fluid production and injection and reduce the risk of not achieving the required flow rates. The technology is less reliant on the availability of a deep aquifer and has potential for application in most areas of the UK[83] (similar to shallow geothermal closed-loop systems). The power output of such purely conductive systems is much lower than for doublet systems, and modelling suggests that under the current UK subsidy regime, only deep wells in selected localities (with high geothermal gradient) can achieve economic returns.[84] The technology is still in its infancy and only a few systems have been implemented worldwide and with mixed success.[85] Other technologies for heat exchange in single wells include conventional U-pipes as used in shallow closed-loop systems), but lower water volumes in these system means that they deliver lower heat loads for the same depth of borehole.

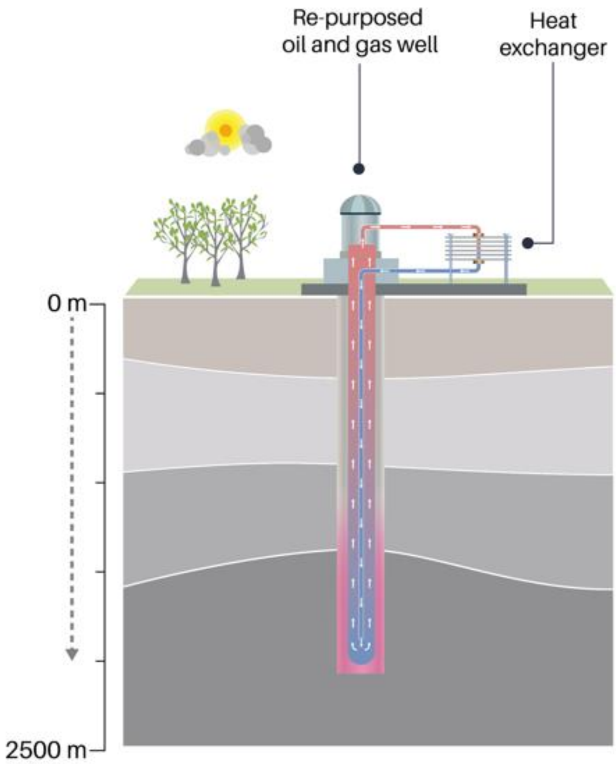

Figure 9: Single, coaxial borehole heat exchanger for geothermal heat production (© UKRI 2022)

Enhanced geothermal systems

Deeply buried rocks (up to 9 km depth) in the UK have enormous theoretical potential for geothermal power generation[86] through enhanced geothermal systems (EGS) – 2% of which could cover the UK's energy demand for more than 1,000 years.[86] However, high drilling costs and risks currently restrict the economically-viable capacity for geothermal power generation to heat producing (radiogenic) granites[87,88] in Southwest England, Northern England and Scotland (pink areas in Figure 8). These still constitute a notable resource.[38,42] Geothermal power generation potential in the heat producing granites in GB is estimated as 2,280 MW,[86] although some experts regard this as an overestimate. There is consensus, however, that UK geology could support several (tens of) geothermal power stations and that a target of 500 MW of installed capacity could be an achievable target.[89] For comparison, Europe's largest gas-fired power station at Pembroke has a capacity of 2,200 MW and can generate electricity for around 3.5 million homes.[90,91] In Northern Ireland, the granites of the Mourne Mountains are considered a potential EGS target, although the overall potential for EGS in Northern Ireland remains poorly understood.[58]

Enhanced geothermal systems (EGS) are unconventional geothermal systems. They are created where there is hot rock but insufficient natural fluid and/or permeability within the system to transport this heat to the surface. Different definitions exist for EGS.[92] In the context of this note, the term EGS is used to describe naturally fractured geothermal systems where hydraulic and/or thermal fracturing (injection of water under high pressure) or acid dissolution are used to enhance existing or create new fluid pathways.[62] EGS are typically developed for power generation, which requires temperatures of more than 160°C, although it can also provide heating to nearby buildings to make the system more profitable. The basic design consists of a well doublet drilled into a fracture system (Figure 10). A closed circulation system is created by extraction of water from the production well (producer) and re-injection into the second well (injector).

There is no operational EGS scheme in the UK at present, but two projects are under development in Cornwall and a further four projects have been announced.[93] The United Downs Deep Geothermal Power (UDDGP) project, located near Redruth in Cornwall, consists of two wells drilled to vertical depths of 5,057 m and 2,214 m, respectively, encountering temperatures of nearly 200°C in the deeper well. The project plans to supply 3 MW electricity to the grid and distribute 12 MW of heat to a range of potential users (including a new housing estate, a tropical rum distillery and a direct lithium extraction plant). The Eden Geothermal project, also located in Cornwall, has drilled to similar depths as UDDPG to provide heat to the Eden Project,[94] as well as for electricity generation. Drilling of the first well was completed in October 2021 (Figure 11).[95]

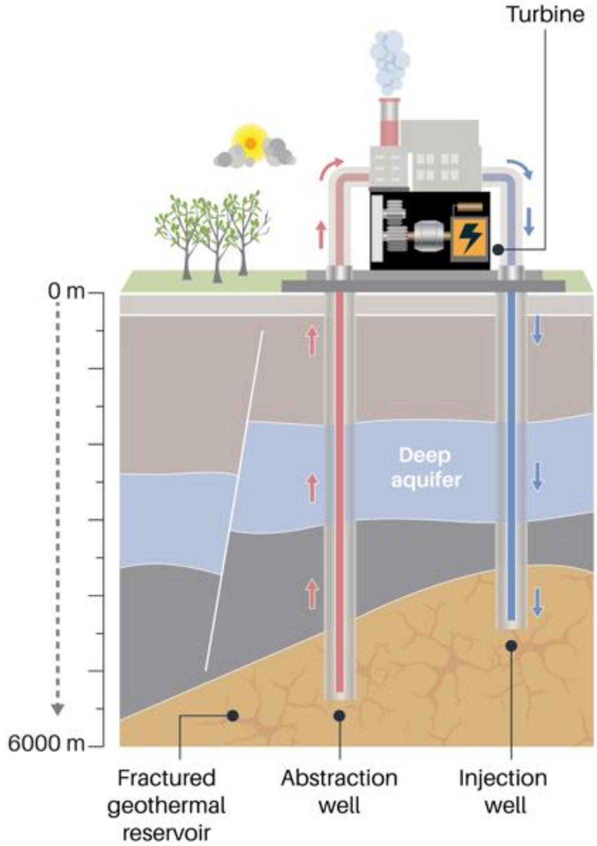

Figure 10: Geothermal doublet drilled into a deep fracture system to create an enhanced geothermal system (EGS) (© UKRI 2022)

2 Potential role of geothermal energy in the UK

The UK's Climate Change Committee predicts that around 20% of UK heat will need to come from heat networks by 2050 if the UK is to meet its carbon targets cost-effectively.

In countries like Germany, geothermal technologies make an important contribution to reducing carbon emission from heating (saving 3.5 million tonnes of CO_2 equivalent in 2021, 1.5% of the total annual carbon savings from renewable technologies),[96] including geothermal heat networks (Box 3). The UK's Climate Change Committee (CCC), an independent advisory body, predicts that around 20% of UK heat will need to come from heat networks (PN 632)[97] by 2050 if the UK is to meet its carbon targets cost-effectively.[98] These will use a combination of clean and affordable technologies[99] when and where they are available. Geothermal technologies, from ground source heat pumps to deep geothermal plants, can be connected to heat networks. They have one of the lowest carbon footprints for space and water heating (PN 532),[100] but the use of geothermal sources for supplying heat networks is only just emerging in the UK (Box 2).

Shallow geothermal heat networks are considered in the Sixth Carbon Budget (CB6).[101] Underpinning modelling assumes that 20–25% of heat pumps will be GHSPs, implemented as shared ground-loops (ambient heat networks) rather than as individual GSHPs. Deep geothermal heat or power generation were not included in CB6 due to a lack of up-to-date evidence on levelised costs of energy (the cost of building and operating a generation asset, expressed as a cost per unit of electricity generated) or new operational schemes. The 2050 Pathway Review[102] and the Heat and Buildings Strategy[103] identify geothermal district heating as an area that needs further research in the UK.

Box 2: Examples of UK Geothermal heat network developments

Geothermal energy can support heat networks across a range of scales. Examples of developments of such heat networks in the UK are given below.

1. **Shared ground-loop arrays and open-loop GSHP heat networks** In the London Borough of Enfield, shared ground-loop arrays supply 400 flats within eight 12-storey tower blocks. Heat is delivered via a 'district' array of 16 shared ground-loop systems with each system typically consisting of seven boreholes. The ground-loops are connected to individual heat pumps (called 'Shoebox' heat pumps because of their small size) which were retrofitted to each flat, replacing the existing electric underfloor heating system. While reducing heating and hot water bills by more than 50%, tenants keep full control of their own heating and hot water. They can also select and switch electricity supplier and tariff to maintain lowest possible running costs. The system is estimated to save 773 tonnes of carbon emissions per year compared with the

previous system.[104] An open-loop district heating system is currently being developed at Northern Gateway in Colchester (Essex). It is intended to extract heat from the underlying chalk aquifer to supply 5.5 GWh of low-carbon heat per year to homes, offices and a healthcare centre.[105] Another scheme incorporating GSHP in district heating in London is currently going through the licensing process.

2. **Mine water geothermal heat networks**
Seaham Garden Village is a new development of housing, a school, shops, and medical and innovation centres that will have district heating supplied from the Dawdon mine water treatment scheme. The pumped mine water is at a temperature of 18–20°C and has a potential heating capacity of 6 MW, supporting a district heat network of around 1,500 new homes. The government has provided financial support to the council through £3.8 million of Heat Network Investment Programme funding, a £150,000 Garden Village grant and technical support from the Coal Authority, stimulating over £170 million of private sector funding.[121] The project has an estimated lifetime saving of 64,000 tonnes of CO_2 over a 25 period. This equates to annual savings of about 2,600 tonnes of CO_2 compared with gas heating.[106]

3. **Geothermal district heating networks**
The Southampton District Energy Scheme (SDES) is the only operational system in the UK that delivers heat from a deep geothermal borehole to a district heating (and cooling) network. Operational since 1986, the 1.7 km deep geothermal well abstracts water at a temperature of 76°C from the deep sedimentary aquifer beneath the city. The heat feeds into the SDES that supplies heating, cooling and electricity from a mix of sustainable sources to more than 45 commercial and residential energy users across Southampton.[107] In Stoke-on-Trent, the city council has given planning approval for a 14 MW 'deep geothermal' energy project in the Etruria Valley. The project will supply low-carbon heat to the UK's first at-scale, deep geothermal heat network. It has the capacity to provide heating for more than 10,000 homes, but initial plans suggested that it will harness 45 GWh of geothermal heat per year[108] (sufficient to provide heating for around 4,000 homes). The project will drill two wells to an approximate depth of 3,800 m beneath Etruria Valley where hot water at temperatures of more than 95˚C is expected.[109] The project has been delayed multiple times since its announcement in 2014.[110] A Memorandum of Understanding has recently (September 2021) been signed between the energy company SSE and GT Energy UK Ltd/iGAS for progressing the development of the geothermal district heating project in the next 12 months.[111]

With 12,000 communal heat networks and 2,000 district heating schemes already operational in the UK,[112] predominantly supplied by gas boilers (52%) and gas-fired combined heat and power (CHP, 32%) (PN 632), there is an opportunity for deploying geothermal technologies to supply heat to new and existing heat networks in areas where the geology is suitable (Figures 3, 6 and 8). Where they coincide with built-up areas, deep geothermal resources can provide heat for city-wide district heating.[97] In Paris, utilising heat from the deep aquifer beneath the city is supplying geothermal heating to around 250,000 homes (more than 2 million people)

The UK coal mining legacy has created a low-temperature geothermal resource beneath many UK cities that can be exploited via ground source heat pumps without drilling deep wells.

via 50 heat networks.[113] Munich supplies around 50,000 homes with geothermal heating, saving about 75,400 tonnes of CO_2 per year compared with gas (Box 3).[114] Development of such direct-use heating schemes requires drilling of deep wells (greater than 1 km depth) to achieve the required temperatures. The Southampton District Energy Scheme is currently the only UK heat network using a deep geothermal source (at 1.7 km depth)[115] but there are plans to use deep geothermal heat in Stoke-on-Trent[116] (Box 2).

The UK coal mining legacy has created a low-temperature geothermal resource beneath many UK cities (Figure 6) that can be exploited via ground source heat pumps without drilling deep wells. A number of heat networks are currently being developed using mine water sources[117,118] or ground source heat pumps.[116] There is increasing interest in 5th generation heat networks (PN 632), which consist of a shared ground-loop that moves heat between the ground and individual heat pumps contained within each property. This differs from the traditional centralised district heating network, as each property is fitted with its own heat pump unit, rather than relying on a centralised plant. In addition to creating a familiar ownership experience (users fully control their heating and bills), these systems have the additional advantage that they do not require expensive insulated pipes or an energy centre.

Box 3: Case study: Munich Geothermal District heating

The aquifer beneath Munich is widely used for geothermal heating by the city and surrounding communities.[119,120] Between 1998 and 2018, 26 deep geothermal projects have been realised in the wider area (the south German Molasse Basin) with 100% of the heat projects and 75% of the power projects being successfully completed (three power projects were not completed, two because water flows were too low and one because the natural gas content in the aquifer was too high).[121] The largest user of the resources is Munich's utility provider, Stadtwerke München (SWM), who set the goal for Munich to become the first European city supplied by a 100% geothermal energy district-heating network by 2040. The State of Bavaria has set a goal to generate 25% of heat from geothermal energy by 2050.[122] SWM already supplies around 50,000 homes with geothermal heating, achieving carbon savings of 75,400 tonnes per year (compared with gas).[114] A new plant is expected to go online in 2022 which will supply a further 80,000 households via the city's extensive (900 km) district heat network.[123]

The success of the geothermal developments in Munich and the surrounding area has been attributed to three supporting factors:

1. The Bavarian Geothermal Atlas shows where favourable conditions exist for the exploitation of geothermal heat or electricity generation, including detailed maps of depths, thickness and temperatures of the resource. Funded by Bavarian State Ministry for Economic Affairs, Infrastructure, Transport and Technology, the atlas is available free of

charge. It is said to have contributed considerably to the wider exploitation of geothermal energy in the region by highlighting the available potential to municipalities, utility companies and private investors.

2. **Long-term government support** and financial incentives are believed to have been instrumental in improving the economic case for geothermal developments during early stages of market development. Support was available from both national and state government, including grants for drilling geothermal wells (up to €5 million per doublet), plant development (up to €2 million per plant) and development of the district heating network (up to €1.5 million per project) as well as low interest loans and insurance schemes for geothermal projects to cover unforeseen technical risks.[124] Financial support was of particular importance to early projects undertaken by local authorities[119] and smaller communities. In addition to improving the economic case, government support also provided the pledge for banks to sign off on large loans, such as the €50 million loan needed for developing the municipality-run scheme in Holzkirchen (near Munich), which is now generating revenues of more than €10 million per year.[125]

3. **Research and Innovation.** To enable upscaling of geothermal operations to the entire city, an €8 million research project called GRAME[126] was set up (50% coming directly from the Federal Ministry for Economic Affairs and Energy (BMWi)'s Innovation-Through-Research programme)[126] to support the geophysical data acquisition, experiments and modelling that were needed to improve understanding of the geothermal resource. The growing availability of data, experience and knowledge from completed research and commercial projects as well as drilling innovation led to a reduction in geological risks and to an improvement in drilling efficiencies. Reductions in drilling time directly impacted the drilling costs, which reduced from €1,400 to €1,100 per drilled metre.[127] Improved characterisation of the geothermal resource, better understanding of projects risks and cost reductions for drilling along with a maturing geothermal market means that deep geothermal heat projects in and around Munich are now less reliant on government subsidies.[119]

3 Environmental considerations

Geothermal energy operations can be associated with a number of environmental impacts affecting subsurface temperatures, groundwater resources and gas emissions. Geothermal schemes can also carry some drilling and operational risks.

3.1 Subsurface temperature changes

The operation of geothermal schemes will result in temperature changes in the subsurface. For example, long-term injection of high volumes of cooled (ground)water into deep hydrothermal or EGS systems have been reported to cause gradual cooling of these geothermal reservoirs over the lifetime of the geothermal plant.[128–130] In the context of deep geothermal operations, subsurface cooling needs to be considered as part of reservoir (and resource) management but is unlikely to impact the surface environment.

In shallow geothermal systems, heat exchange between GSHP systems and the subsurface can lead to local temperature changes of ±4–10°C in the area surrounding the GSHP.[20,131,132] This so called thermally affected zone (TAZ) can reduce the system's own efficiency[133] or that of other nearby GSHP systems.[134–136] The risk of such thermal interference is heightened in areas of high system density. In central London, many large GSHP schemes (used predominantly for cooling of commercial buildings) are within 250–500 m of each other, and the proximity and density of these systems (in conjunction with the local hydrogeology) makes interference effects unavoidable.[134,137] While the GSHP can continue to operate when thermal interference occurs, the scheme may become unviable if its efficiency falls below economic levels. Risk of interference can be reduced through managing the heat resource in the subsurface[134] so that systems are not approved where there is risk of 'heat derogation' on existing schemes, similar to existing water abstraction licensing. Adopting such a management system would require resource planning tools, backed by appropriate regulation, including recognition of heat as a natural resource.

Many commercial buildings use groundwater for cooling and release large heat loads to the subsurface, which have been linked to long-term temperature rises beneath some cities.[17] While groundwater temperatures in central London have increased by 2–3°C since 2005,[138] the contribution of GSHPs cannot be quantified as heat loads from these systems to the subsurface are not regulated or registered, and the locations of closed-loop systems (which currently do not require any licences or permits) are largely unknown.[139] Furthermore, the impact of GSHPs on local groundwater temperatures will vary depending on the size of the scheme and how fast the heat/cold can dissipate in the subsurface. While temperature monitoring data for some open-loop systems in London suggest a contribution of those systems to the temperature increase observed in the groundwater beneath London, monitoring of an open-loop GSHP in central London over six years did not show any discernible changes in surrounding groundwater temperatures.[140]

3.2 Impact on groundwater resources and quality

Thermal energy from the subsurface is extracted via a heat carrier fluid. Geothermal doublet and open-loop GSHPs use groundwater as heat carrier. These systems remove groundwater from the subsurface (along with the heat contained within) as part of the geothermal operation. Usually, the water is returned to the groundwater body (aquifer, see definitions in POSTbrief 40) after the thermal energy transfer has taken place, so that net impacts on the groundwater resource quantities are minor. Nonetheless, most open-loop GSHPs in England and Wales still require a full abstraction licence (for removing water from the aquifer)[141] and a groundwater discharge activity environmental permit (for retuning the water to the aquifer).[142] The system is designed to help the regulator to manage water resources in a way that is fair to all users, and to prevent environmental pollution.[143] In Scotland, abstraction and discharge from open-loop systems can be authorised under General Binding Rules (GBR) without needing a licence or permit, as long as the system returns the abstracted water into the same geological formation from which it was abstracted, and the water's chemical composition has not been altered.[144]

Closed-loop systems transfer heat by circulating a refrigerant mixture (typically consisting of water, anti-freeze compounds and corrosion-inhibitors) around an array of closed-pipe loops in the ground (borehole heat exchanger). Although these systems do not use groundwater directly, incorrectly installed or defective systems may adversely impact groundwater quality, for example through the release of anti-freeze components and other additives from leaking pipes,[145,146] that may be harmful. Reports of leakage or pollution from closed-loop GSHPs are rare.[140] The extent to which such incidents occur in the UK is difficult to assess as closed-loop GSHP systems (at the time of writing) are not regulated or monitored, and the locations of these systems are largely unknown.

Where aquifers are excessively used by GSHP cooling systems, seasonal changes in groundwater temperatures of 4–10°C have been observed and have been linked to minor changes in groundwater chemistry and microbiology.[131,132,147] To protect water quality, some cities (like Berlin, Germany) do not permit the use of aquifers for geothermal (GSHP) cooling.[148]

Water quality in abandoned mines can vary with depths within the same mine water system, including some poor quality waters. Mine geothermal operations may lead to pollution through mixing of different quality waters (mainly when injecting water at different levels within the mine) or through the intrusion of deep, saline waters as a result of pumping.

Pumped water from deep geothermal target may also contain naturally occurring radioactive material (NORM), especially in granites that are naturally enriched in radioactive elements like uranium. Where NORM is anticipated, a RSR (Radioactive Substances Regulations) permit is required to ensure such materials are managed in a controlled manner.

3.3 Emissions and microbial risks

Deep geothermal fluids can contain some gasses such as hydrogen sulphide, carbon dioxide, helium, hydrogen and methane,[149] that are released when the fluid comes in contact with the atmosphere. Carbon dioxide emissions from geothermal electricity plants, including very hot systems for direct power generation by steam, are around 4–74 grams of carbon dioxide equivalent per kilowatt-hour (gCO_2eq/kWh) globally.[150] Although not insignificant, this is considerably less than CO_2 emissions from conventional electricity generation using coal (greater than 750 gCO_2eq/kWh) or gas (greater than 350 gCO_2eq/kWh)[151] (PN 383). Geothermal systems in the UK are likely to contain very small amounts of gas. In some places, like Cornwall, radon gas may be released from the drilling fluids produced, but this will rapidly diffuse into the atmosphere and is not generally considered a safety risk outdoors. Preventing exposure of geothermal fluids to the atmosphere altogether, for example by circulating them in closed-loop pipe systems, can minimise such emissions during operation of the system.

Ground source heat pump equipment as well as some geothermal engines for power generation (Organic Rankine Cycle systems) contain fluorinated gases (F-gases) for facilitating the heat exchange. These potent greenhouse gases may leak if systems are installed, operated or decommissioned incorrectly.

GSHPs require about one unit of electricity to generate up to four units of heat. Emissions from these systems are dependent on the electricity source that is used for powering their operation. They are likely to reduce as the UK power system decarbonises in line with the Government's plan to reduce carbon emissions associated with electricity production to 2 gCO_2/kWh in 2050 (down from current emissions of 222 gCO_2/kWh which have remained unchanged for the last 2–3 years).[152]

Some thermally polluted or naturally heated water bodies, including geothermal springs and recreational waters, can support growth of microorganisms like thermophilic amoebae (single cell organisms that thrive in relatively high temperatures of 30–40°C, including one species that can cause brain disease in humans). A few rare cases have been reported worldwide where exposure to warm, usually untreated or poorly disinfected water has caused fatal brain disease in swimmers,[153,154] including one case at the King's Spring in Bath in 1978.[155] Today, the Roman Baths are no longer used for bathing, but the springs are tapped at depth by boreholes that deliver clean thermal water to the drinking fountain in the Roman Baths museum and the local spa complex.[156]

3.4 Drilling and operational risks

Environmental impacts and risks related to the drilling, installation and operation of geothermal wells vary depending on the type of geothermal installation and drilling depths. For the drilling of ground source heat pump wells, risks are generally extremely low, similar to those associated with the drilling of ground investigation boreholes or water abstraction wells. In areas of specific geological and hydrogeological conditions, drilling operations can have an enhanced risk of inducing ground swelling (uplift) or subsidence which, if not mitigated, can lead to serious damage.

The most well-known accident occurred in Staufen (Baden Württemberg, Germany)[157] where the drilling for a closed-loop borehole heat exchanger (BHE) resulted in uplift of the town centre and serious damage to historical buildings due to defects in the borehole fill (grout).[158] In 2011, the State of Baden Württemberg issued new guidelines for the installation of BHEs[159] that consider the specific geological settings. Since then, there have been no further reports of damage related to BHE installations in the area.[158] As with boreholes drilled for other purposes (water abstraction), GSHPs have also been linked to possible risks of cross-contamination between separate groundwater bodies (aquifers)[133] during drilling or through connecting aquifers via defective borehole filling.[131]

Figure 11: Drilling at Eden Geothermal Limited's site at the Eden Project in Cornwall (part funded by the European Regional Development Fund). Photo credit: Corinna Abesser

In England and Wales, the installation and operation of the majority of GSHP systems is currently not regulated and there is no requirement to register their locations, except when applying for the Renewable Heat Incentive scheme (RHI). GSHP installations that claim government support (for example through RHI) have to comply with the drilling and installation standards defined by the Microgeneration Installation Standard: MIS 3005[160] for closed-loop BHEs. Additional standards and good practice guidance for different types of GSHP installations have been issued by the UK Ground Source Heat Pump Association (GSHPA)[161] and the Chartered Institution of Building Services Engineers (CIBSE).[162]

The drilling for and operation of deep (1–5 km) geothermal schemes bears some risk of triggering very small earthquakes (micro-seismicity). Such events are most commonly observed in connection with enhanced geothermal systems (EGS)[163] which may inject water at high pressure into underground fault zones to push water into the existing system of natural fractures or cracks to open them up (not to create new ones).[89] Most seismic occurrences related to geothermal operations are minor in comparison to natural tectonic earthquakes or other types of induced seismicity related to mining, surface water impoundment, hydrocarbon exploitation or carbon capture and storage (CCS).[163–165] In rare cases, induced seismicity from geothermal operations in other countries has caused injuries and economic damage[166–169] or lead to public nuisance and concern.[163] The size of a micro-seismic event and how it is felt at the surface is influenced by the local geology. In the UK, the geology is relatively stable and, as a general rule, deep geothermal projects are not expected to cause events that are larger than events that would naturally occur in the area.[89] The United Downs Deep Geothermal Power (UDDGP) project in Cornwall, the UK's first development of an EGS, operates a network of seismometers that continuously monitors seismic activities around their site. The network detected small induced seismic events with local magnitudes (M_L) of -1.0 to -0.5 during drilling of the wells[170] and a number of minor events of M_L 1.1. – 1.7 during water injection and testing of the well. These events did not cause any damage but a few were heard and sometimes felt by some local residents.[171] For comparison, enthusiastic dancing by an audience of about 40,000 people during the performance of the popular ska band Madness at the Reading Festival (Southern England) in 2011 induced micro-seismicity equivalent to an earthquake of M_L 0.4 at 1.5km distance from the site[172]. According to the British Geological Survey, earthquakes with magnitude less than 2 are not usually felt. Earthquakes with magnitudes less than 1 are hardly ever felt. The smallest earthquake felt in the UK had a magnitude of 0.5 and was felt by one person. Earthquakes with negative magnitudes are never felt.[173] Injection testing of the 4,871 m deep (vertical depth) well at the Eden Geothermal project resulted in over 300 low level micro-seismic events, including one event on 9 March 2022 that was heard and felt by people in the local community. The event had a local magnitude of 1.7 at a depth of over 3,700 m. Magnitude is not the main factor that determines whether an event is felt or heard at surface; this is dependent on the Peak Ground Velocity (PGV) measured in millimetres per second (mm/s). PGV is a measure of ground vibration (see Section 5.2.5), and the PGV associated with this event was 1.56 mm/s.[174]

4 Developing a UK market for geothermal energy

4.1 Route to market

There is consensus among geothermal stakeholder groups in the UK that a 'route to market' that would include legislative, revenue or subsidy support is needed for the geothermal sector to develop in the UK, both on the demand side (heat users) and the supply side (developers, drillers, installers).

The Government supports renewable technologies through a range of policy measures, which are described in Section 5.1 and Box 4 below.

Geothermal energy targets

Stakeholders have identified a need for clear targets for UK deep geothermal and GSHP development as well as stable, long-term policies and incentives to support the industry,[175] especially during early stages of market development. Clear targets, competitive subsidies and sustained, long-term government support have contributed to rapid cost reduction for offshore wind in the UK (PN 602)[176] and are regarded as the main reason that the UK is now amongst the world's market leaders in this field.[177]

The adoption of a target of 12 operational deep geothermal projects for 2025 has been suggested in a recent industry report.[178] The report states that these could provide heating to 50,000 homes, create 1,300 jobs and generate more than £100 million of investment in towns and cities centred in the North of England, Midlands and South-West.

Assuming favourable market conditions, including government intervention, and based on UK drilling capabilities in the oil and gas sector (12–15 wells per year), the report suggest that 360 sites could be established by 2050, providing: £1.5 billion of investment; 15,000 GWh of heat for over 2 million homes; and an annual carbon saving of 3 million tonnes.[178]

Government interventions to support such targets could include upfront grants, feed-in tariffs and subsidies, a geothermal risk mitigation scheme as well as greater funding for research and development, although there is no consensus in the industry which of these should be prioritised.

Risk sharing

Geothermal risk mitigation schemes are highlighted in recent reports[175,179,180] as one of the key mechanisms for stimulating the development of deep geothermal schemes,[175,181] tackling pre-development risks for geothermal energy[182] and leveraging private sector investment. France, Germany and the

Netherlands have used national risk insurance schemes to attract private capital by de-risking drilling and construction, which account for up to 65% of the total project cost (Figure 13). For every €1 paid by the French government, €42 was leveraged by private investors.[183]

Government undersigning project risks is not unprecedented in the UK. A recent project where the UK Government has stepped in as an insurer is the Thames Tideway project which has procured a contingent support package from the Secretary of State for Defra that covers a variety of risks that could not be efficiently covered by the insurance market.[184]

Legislative support

Support for wider technology adoption could also be driven by combining incentives with regulation. Such approaches have been used successfully in the past, for example in the UK transition from town gas to North Sea gas in the 1960s and 70s that was realised through a mandatory program of appliance replacement with distinct targets and a mix of funding from the government and home owner contributions.[185] More recently, the decision by the Greater London Authority in 2019 to define lower overall building carbon targets as a consideration to planning[186] has resulted in a significant shift from gas CHP towards low-temperature and ambient shared-loop networks[40] in multi-occupancy developments in London.

The Future Homes Standard (FHS)[187] will come into effect in 2025 (pending approval of its legislative basis by Parliament in 2024) and will require new homes in England to be heated by a low-carbon heating source. In the Netherlands, a similar policy introduced in July 2018 (preventing new-builds to be connected to the gas grid) was found to create new opportunities for the geothermal market as heat pump-based technologies were the most favoured alternative to fossil fuel heating.[188] While the FHS is welcomed by the industry, there are concerns about the ability of the UK's manufacturing capacity, supply chain and skills to ramp up the installation of heat pumps with calls for support schemes to be developed promptly.[189] According to a recent mine energy consultation commissioned by the North East Local Enterprise Partnership on behalf of the Mine Energy Taskforce[190] "some developers believe that the government might yet abandon or delay the commitment to exclude fossil fuel-based heating" leading to a recommendation for clear, consistent and unambiguous policy messaging from government.

4.2 Local and regional heat planning

Geothermal energy resources are potentially accessible in all parts of the UK. Their role as a low-carbon heating source will differ according to local context such as available resources, and existing and planned infrastructure. Effective deployment of geothermal technologies will require local and regional energy planning that considers the availability of local geothermal sources and opportunities, and assesses their benefits in terms of scalability, longevity of energy supply, and cost of energy against other available low-carbon sources. Planning authorities will also have to consider potential conflict with other underground uses such as mining rights. Cornwall County

Council, which has considered geothermal resources (mine water and deep geothermal) as part of their local planning,[191] assigns safeguarding areas to protect its mineral and geothermal resources.[192] For deep geothermal they concluded that development of the resource in Cornwall is still too immature to warrant identification of areas of deep geothermal resource for safeguarding.[191]

Heat network zoning

Heat network policy is largely devolved, although some aspects are reserved to the UK Parliament.[193] A new heat network zoning framework is currently being developed for England (announced in the Government's 2020 Energy White Paper[194]). It entails the identification and delineation of areas which can be readily connected to a low-carbon heat network. Led by local authorities, who will be responsible for designating heat network zones in their area, it is expected to enable local and regional heat planning. Local councils must have completed their designation of heat network zones by 2025. Mandating connection for certain categories of buildings to heat networks as part of heat zoning (as suggested in the BEIS proposal for heat network zoning)[195] could provide enough customers to remove the uncertainties for developers around future demand,[196] which has caused failure of some geothermal developments in the past.

Local authorities in Scotland already have the statutory power to designate 'heat network zones' under the Heat Networks (Scotland) Act 2021.[197] National methodologies for heat zoning are in development in England and Scotland, including full public consultations[198,199] which closed in November and December 2021, respectively.

Wales has introduced a heat network policy in the context of the spatial planning document the National Development Framework, Future Wales.[200] While prioritising areas with greatest heat network potential, it highlights the role of planning authorities in identifying and implementing opportunities for heat networks using renewable, low-carbon or waste heat energy sources.

Northern Ireland's Department for the Economy (DfE) sees significant potential for increasing numbers of low-carbon heat networks in Northern Ireland through using geothermal energy. It is currently consulting on a market framework for heat networks,[201] considering an approach to mandate heat planning, including zoning.

Identifying geothermal opportunities

For local authorities to be able to identify and use the geothermal heat potential within their area requires data and information about the available resources (as held by organisations like the British Geological Survey and the Geological Survey of Ireland) to be brought into a format that is accessible for local energy planners.

Dialogue between planners and researchers, as well as funding is likely to be needed to make this possible ahead of anticipated deadlines linked to heat network zoning. Details of the proposed heat network zoning framework for England and eligible heat sources are not yet known, but it is seen as important by the industry and stakeholders that deep geothermal as well as low temperature heat resources (such as ambient heat networks) are included. Although initial installations to access a geothermal heat source might be more expensive, the accessible heat resource can be large, and its availability is not time-limited, unlike for example waste heat which relies on the availability of a specific industrial process or power plant.

Jobs, skills and training

As well as emissions savings, geothermal projects can provide economic stimulus and contribute to job generation. In Germany, the geothermal industry has generated €14.9 billion since 2000[96] and created 24,500 jobs.[202] Geothermal projects create jobs at all stages of the supply chain. Up to 30 direct jobs are estimated for a (deep) geothermal heating project and 100 jobs for an electricity project in areas such as exploration, construction, operation & maintenance, planning, and research (Figure 12).[178] Indirect jobs will come from industries that supply materials and services, including manufacturing (for example steel for borehole casing), drilling fluids and parts, heat pumps, and pipe networks. In the Netherlands, two to three indirect jobs were created for every direct geothermal job.[203]

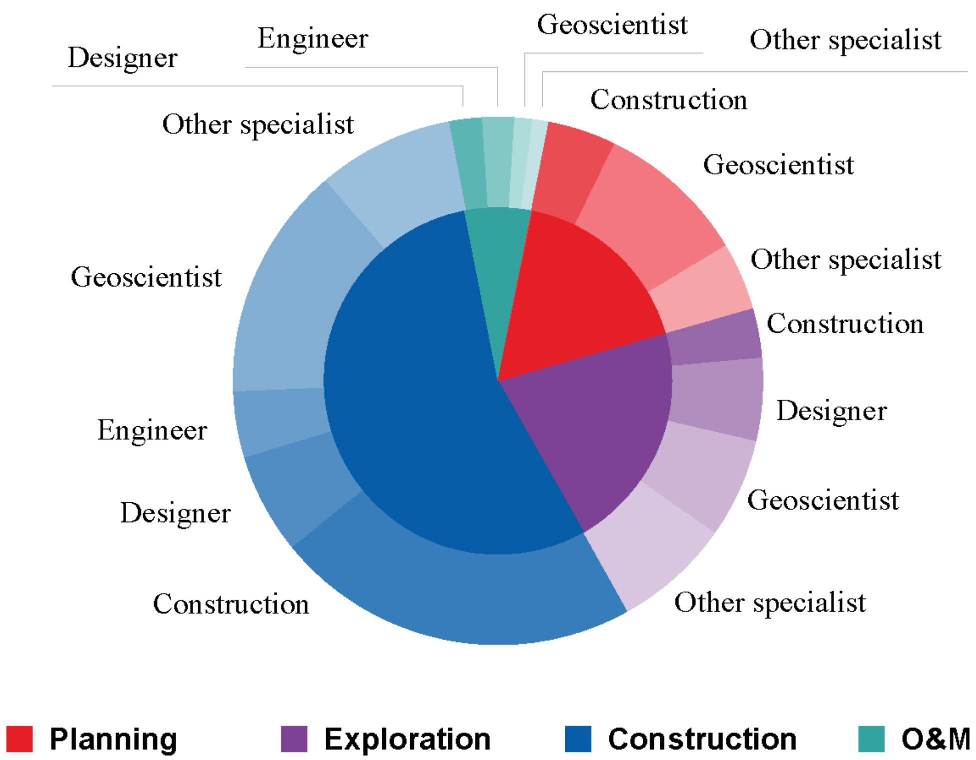

Figure 12: Direct jobs for a typical geothermal project (Source: ARUP)

Opportunities for local job creation

Many of the UK's deep geothermal prospects (Figure 8) are in areas that have low economic activity, high levels of unemployment and few job opportunities[204] such as North East England and Cornwall. Many of the UK's largest urban centres are above areas of former coal mining activity (Figure

6), and there is potential to "give a second life to coal mines" and to create employment in these areas through geothermal schemes.[52] It is estimated that 360 deep geothermal projects in the UK (by 2050) could create over 10,000 direct jobs and 25,000 indirect jobs.[178] In addition, implementing the 42 mine energy projects currently on the Coal Authority's books could deliver almost 4,500 direct jobs and a further 9–11,000 in the supply chain.[190] Requiring similar skillsets and supply chains as hydrocarbon exploration, geothermal projects could offer direct employment opportunities for employees transitioning from the oil and gas sector.

However, while the UK already has some cross-industry expertise, its geothermal service industry, supply chains and specialist skills in geothermal drilling are not sufficiently developed. Ongoing geothermal projects in the UK therefore source their drilling rigs and crews, supplies and services outside the UK, adding extra costs and potential interruptions to projects.

Skills development

There are approximately 279,000 heat pumps (87% air source heat pumps, 9% ground or water source, 4% hybrid heat pumps) installed in the UK (estimated for 2020), supporting more than 2,000 full-time jobs.[205,206] The 2020 Energy White Paper[194] has set a target to install 600,000 heat pumps a year by 2028 - a 20-fold increase on current installation rates of around 30,000 heat pumps per year.[206] It does not specify separate targets for ASHPs and GSHPs, but these systems generally require similar components, manufacturing techniques and skills. Meeting the 2028 target will require considerable growth in the manufacture, supply and installation of all types of heat pumps - sectors that currently experience skills shortages. The UK is said to have approximately 1,200 qualified heat pump installers.[189] To meet installations targets, the Heat Pump Association estimates that 12,400 qualified installers will be required by 2025, increasing to 69,500 by 2035.[207] The heat pump industry is confident in being able to deliver this capacity, for example, through retraining of registered gas engineers, but has said that the "right signals" are needed from government as well as support for market development.[207]

Building supply chains

There is limited manufacturing capacity in the UK for heat pumps,[189] although 41% of the UK market share for GSHPs is occupied by Kensa which manufactures their heat pumps in the UK. According to recent research on heat pump manufacturing,[208] demand alone is unlikely to attract new manufacturers to the UK. Other aspects such as a clear strategy and commitment from government, including long-term, consistent policies that provide clarity on the need for heat pumps as well as a stable regulatory system were identified as key requirements for making the UK attractive to heat pump manufactures.[208] The government is currently consulting on market-based mechanisms to support the transition to low-carbon heat and the wider rollout of heat pumps.[209] Other supply chain constraints, identified by a recent mine energy consultation carried out by the North East Local Enterprise Partnership,[190] include a lack of information relating to the available geothermal resources, key resource variables (depth, temperature, volume), indicative drilling and borehole costs, as well as the risks associated with specific site characteristics. While some geothermal resource assessment tools exist,[210,211] stakeholders identified a need for more advanced geographic information system (GIS) tools as well as national-scale, subsurface geotechnical and hydrogeological models to enable early-stage strategic assessments of geothermal opportunities as well as a better characterisation of the subsurface conditions ahead of site selection and drilling.[190]

4.3 Socio-economic factors

Technology recognition

While recognised in principle as a potential supply for heat networks in the UK, the role of geothermal technologies in the UK's energy decarbonisation agenda has not been clearly defined by the UK Government, and geothermal is rarely mentioned in key policy documents, such as the Government's recent British Energy Security Strategy.[212]

While GSHPs are included in the Government's target to install 600,000 heat pumps per year by 2028, other geothermal sources were not considered in the recent BEIS report on opportunity areas for district heating networks in the UK[213] or in the Climate Change Committee's Sixth Carbon Budget and its supporting studies,[214] due to a lack of information about the application of the technology in the UK. The Government's Heat and Buildings Strategy mentions geothermal as a potential heat source,[103] but highlights a need for further research into geothermal district heating in the UK. Stakeholders have asked Government for support to undertake such research to provide better data for deployment of deep geothermal energy in the UK. Under its new Energy Strategy,[215] Northern Ireland's Department for Economy (DfE) has established a Geothermal Advisory Committee (GAC) to provide independent advice to the DfE on the availability of geothermal energy for heating buildings and to support the advancement of geothermal technologies in Northern Ireland.

Project costs and risks

Geothermal technologies have high initial capital costs, ranging from several thousand pounds for a domestics GSHP installation[216] to several million pounds for large geothermal heat schemes (including mine water geothermal).[9,217] However, operation and maintenance costs are very low so, over time, the overall cost of producing heat or electricity is comparable to alternative technologies. The payback periods for geothermal systems can be 5–8 years for domestic GSHPs[216] and 4–20 years for deep and mine water geothermal installations[9] which are generally longer than for conventional heating systems. In the absence of policies to prioritise renewable heating technologies (which will not come into effect until 2025) or the availability of additional benefits like a recognised increase in property value, these time scales are beyond what many homeowners or commercial organisations are currently willing to accept.

For deep geothermal projects, there is the additional geological risk of not achieving the required temperatures or water flows. Together with upfront investment costs, this exploration and drilling risk presents a major barrier to the development of geothermal heat and power projects in the UK. This risk is highest at the start of a project but reduces once a first well has been drilled and more knowledge of the geothermal reservoir becomes available.[175,178] High drilling costs and the risk of failing to locate a viable and sustainable resource were also identified as a barrier for mine energy projects.[190]

Geothermal technologies are eligible to be considered as a sustainable investment under the EU's Sustainable Finance Taxonomy legislation (EU Taxonomy)[218] provided they meet the taxonomy's requirements. While this may attract investors or financing from supporting schemes, there are concerns from industry that the technical screening criteria (TSC) and emissions thresholds for geothermal do not consider features that are specific to geothermal (such as natural emissions or reliance on decarbonisation of transport),[219] and may actually prevent development of geothermal resources in Europe.[220] The UK Government released a roadmap to sustainable investing in October 2021,[221] which outlines the implementation of a similar taxonomy for the UK (UK Green Taxonomy). According to the roadmap, the first consultations on the taxonomy will take place in the first quarter of 2022.

Technology awareness and public acceptance

Overall public acceptance for geothermal energy as a green technology was rated high at the UK Climate Assembly but awareness of geothermal technologies (including GSHP) is generally low

Overall public acceptance for geothermal energy as a green technology was rated high at the UK Climate Assembly,[222] but awareness of geothermal technologies (including GSHP) is generally low,[223] even in areas of active geothermal developments. Potential risks, accountability and trust are the main public concerns with regards to this technology in the UK.[224] However, experience of deep geothermal projects in the UK is limited and there is very little direct research on public awareness and perceptions of the UK population relating to this technology. Studies from countries where deep geothermal technologies are more common suggest that risk of induced seismicity is the most common concern.[225] Such risks were found to be more widely accepted in remote or less densely populated areas compared to urban areas.[225] While mining caused frequent earthquakes in the UK over many years,[165] induced seismicity in conjunction with unconventional oil and gas exploration and production (shale gas) has caused controversy in Europe and the UK. Some researchers suggest that these controversies may influence public perceptions of other technologies, including geothermal energy.[226]

The importance of effective public engagement, education and transparency about the technology including its risks and their mitigation is widely recognised as critical for obtaining community acceptance and trust that would lead to a wider social licence to operate.[227] Early contact with involved communities (which started 3–4 years prior to drilling) and extensive public engagement is regarded as one reason for the geothermal success of the City of Munich (Box 3). Notable achievements include the successful completion of deep geothermal projects at large scale within a dense urban setting and with minimum disruption or public protest – in spite of Germany's strong environmental protest movement which has stopped deployment of many other energy technologies (such as nuclear power, shale gas and CCS) and deep geothermal projects elsewhere.[228] There is also a high level of support for geothermal energy amongst the general public. A public vote in 2017 decided in favour of early decommissioning of Munich's coal power station by 2023, accelerating the transition of the city's district heating network to geothermal energy.

Consumer experience and affordability

Public awareness of domestic, shallow geothermal applications using GSHPs is low,[229] and there remains a strong preference for gas heating compared with low-carbon alternatives,[230] despite the UK's net zero targets. Lack of consumer protection and high up-front costs of low-carbon heating system (including heat pumps) or networks are cited as key barriers to the transition from fossil fuel to low-carbon heating.[97,229,231,232] Until the recent rise in energy prices, potential savings in running costs of GSHPs compared with a gas boilers were limited by the high price differential between electricity and gas created by UK energy policy.[233]

Environmental and social obligations account for about 23% of a domestic electricity bill compared to around 2% for gas,[231] meaning that while heat pumps are more efficient than gas boilers in terms of energy use, in many instances they will be more expensive to operate.[234,235] This is viewed by the industry as disincentivising the uptake of heat pumps. The relatively low cost of gas (until late 2021) has also been identified as a challenge for mine energy.[190] However, the rise in household energy prices, which saw unit costs for gas increase by up to 84% and electricity by up to 35% in April 2022,[236] means that renewable heating technologies such as heat pumps are becoming more competitive. An analysis from March 2022 concluded that an efficient heat pump may now save homeowners up to 27% on their heating bills compared to a gas boiler.[237] In addition, the Heat and Buildings Strategy[103] states that Government plans to reduce the price of electricity over the next decade by shifting levies away from electricity to gas. Details will become available when a decision is taken by the Government in 2022.

Retrofitting heat pumps in existing homes is often not a straightforward option. The need to coordinate groundwork with building and electrical work can make this a complicated project for homeowners, often with little guidance or support from installers or local authorities. As the RHI is coming to an end and combined with the sudden demand created by the Green Homes Grant[238] (now closed for applications) there is rising pressure on heat pump installers that has resulted in local skills shortages. In addition, the building industry is often not set up for delivering GHSP installations as part of wider renovation projects, meaning homeowners often revert to conventional heating solutions.[239]

Although buildings with poor energy efficiency are often regarded as a key hurdle for meeting the 'retrofit challenge',[240] GSHPs have been successfully fitted to a range of social housing[104] that often have poor energy efficiency standards. The main challenge arises from connecting single privately-owned buildings to shared GSHP loops (ambient heat networks) as this requires a behavioural change by individual homeowners to share a common heat source.

5 Policy and regulatory frameworks for geothermal energy

5.1 Government support schemes

In the UK, the Renewable Heat Incentive (RHI) is the principal mechanism to support geothermal heat installations, but it is now closed for new applications – see Box 4 for details of this and other support mechanisms.

The RHI initially resulted in falling numbers of GSHP installations due to tariff imbalances which favoured biomass.[241] Following revision and rebalancing of the tariffs in 2017, the rate of GSHP installations in the UK increased, particularly in larger installations in the non-domestic sector.[242,243] The recent closure of the non-domestic RHI[244] has created a policy gap around large scale heat decarbonisation, slowing down the roll out of renewable heat projects during 2021.[245] Similar sensitivity of the heat pump market to policy decisions was seen in France, whose rapidly growing GSHP sector collapsed dramatically in 2019 (reducing to one tenth of its previous size) in response to changes in the support framework.[246]

A new three-year scheme, the Boiler Upgrade Scheme (BUS), formerly the Clean Heat Grant (CHG), was announced in the Government's Heat and Building Strategy[103] for domestic and small non-domestic installations. The scheme is opening to applications on 23 May 2022, seven weeks after closure of the domestic RHI. Whilst installations commissioned on or after 1 April 2022 are eligible for the BUS, the heating industry fears that the gap in payment will cause cash flow problems for some installers and potential damage to the renewable heating sector.[247]

The scheme offers capital grants for ASHPs, biomass boilers and GSHPs of up to 45 kW. Grant payments are higher than under the CHG, which was criticised for focussing only on small systems as the cost to the consumer for schemes larger than 10 kW becomes too great to make the installation viable.[245] The Government acknowledges that, even with this higher subsidy, paying the additional capital costs is likely to be a challenge for many consumers,[248] considering that installed prices are in the order of £8,750 and £13,200 for an 8 kW ASHP and GSHP, respectively, excluding additional costs related to the heat distribution systems, controls and ground works for GSHPs.[249]

While the simplified approach of changing from a tariff to an upfront grant is generally welcome, the scale of the funding (£450 million over three years) is widely seen as too low[234,250,251] to achieve the Government's targets of 600,000 heat pump installation per year by 2028.[194] A maximum of 30,000 homes per year would be able to benefit from BUS, the same as current installation levels. E3G, an independent European climate change think tank,[252] concluded that an additional £850 million would be needed to meet the target of 600,000 heat pump installations.[251]

The Government expects to see significant reductions in the installed cost of heat pumps of at least 25–50% by 2025, although stakeholders state that more certainty is needed about measures to support the market and ramp up heat pump installations beyond 2025.[253] The announcement by the Chancellor to remove VAT for heat pumps and other energy-saving measures for five years from 1 April 2022[254] has been welcomed by the heat pump industry.[247,255] However, in Northern Ireland the immediate implementation of the 0% VAT policy is prevented by the Northern Ireland protocol.[255]

Geothermal electricity is supported under the Contract for Difference (CfD) scheme, which is the Government's main mechanism for supporting low-carbon electricity generation. There is scepticism regarding the extent to which geothermal can be competitive against other supported technologies, such as offshore wind and Advanced Conversion Technologies (ACT).

Box 4: UK policy and financial support for geothermal heat or power

New and existing geothermal schemes have different sources of subsidy available to them depending on whether they produce heat or electricity:

- The **Renewable Heat Incentive (RHI)** provides a subsidy to applicants for every unit of renewable heat they produce. It closed to non-domestic applicants in 2021 but has been extended to 2022 for domestic schemes. BEIS has been consulting on a market framework (including the Clean Heat Grant) to implement after the closure of the existing subsidy policy.[256,257] No announcement has been made on future support for commercial buildings. This, and the general lack of detail about long-term support for renewable heating technologies in the UK creates a high level of uncertainty for the industry.
- **Contracts for Difference (CfDs)** are the main subsidy for large-scale renewable projects. They are given to developers of eligible technologies who win a competitive auction. CfDs provide a guaranteed price for the electricity that generators sell into the wholesale market, known as a 'strike price'. When the wholesale price is below the strike price, generators are paid the difference. When it is higher, the generator pays the difference back.
- Developers can sell power directly to large consumers under a **Power Purchase Agreement (PPA)**, which can also provide a guaranteed price for a fixed period. For example, UDDGP has agreed a Power Purchase Agreement for the electricity that will be produced by the plant.[258]
- **The Green Heat Network Fund (GHNF)** scheme,[259] announced in the 2020 budget, is a 3-year £288 million capital grant fund for low and zero carbon (LZC) heating and cooling networks (new and retrofits). The scheme will replace **the Heat Network Investment Programme (HNIP)**. It supports all networks that meet its core eligibility criteria

(which includes metrics on technology carbon intensity and minimum heat demand supplied by the network) irrespective of technology. A £10 million transition scheme[260] opened in July 2021 for networks with heat demands greater than 2 GWh per year (urban) or more than 100 connected dwellings (rural) – which are more likely to be served by deep geothermal or mine energy sources instead of GSHPs. Core eligibility metrics have yet to be confirmed for the GHNF full scheme which launches in April 2022. The GHNF main scheme opened its first application round on 14 March 2022. This will be followed by quarterly rounds until the scheme closes in 2025.

- The **Boiler Upgrade Scheme (BUS)**, initially announced as the Clean Heat Grant (CHG), will replace the domestic RHI which ends in March 2022. The scheme offers capitals grants of £5,000 for ASHPs and biomass boilers, and £6,000 for GSHPs for schemes up to 45 kW, including shared ground-loops for non-social housing projects. It will be supported by £450 million of Treasury funding for the three years of the scheme. This would support up to 30,000 heat pumps per year. Separate funding will be made available for social housing schemes, but details have yet to emerge.
- The **Electrification of Heat Demonstration Project** (£14.6 million) installed and monitors 750 innovative heat pump systems across a range of different housing types to demonstrate the feasibility of a large-scale roll-out of heat pumps in Great Britain. System installation phase was completed in 2021, monitoring will be undertaken for one year, finishing in 2022.
- The **Heat Network Delivery Unit (HNDU)**[261] provides support for local authorities in England and Wales for carrying out techno-economic feasibility studies and specialist consultancy work around provision of heat (including from geothermal sources) to heat networks.
- The **Rural Community Energy Fund (RCEF)** [200] is a £10 million programme which supports rural communities in England to develop renewable energy projects (including geothermal), which provide economic and social benefits to the community.

Even with policy frameworks in place, other market barriers - high upfront costs, capital constraints for consumers, lack of technology recognition, and uncertainty about a technology's performance - can still prevent widespread adoption.[262] Additional measures like new business models may be necessary to increase market adoption of geothermal technologies (see Section 6.3).

Furthermore, learning from other major infrastructure transitions, like gas grid repurposing, introduction of condensing boilers or personal transport transitions, has shown that relying on consumer and/or market choice alone can result in varied and uncertain rates of change.[263] Therefore, to meet statutory net zero targets, a hard date for technology phase-out may be needed (see Section 4.1.3) possibly ahead of economic lifetime or natural replacement cycles.[263] In Scotland, several additional funding streams are available for geothermal energy technologies, including the Low Carbon Infrastructure Transition Programme (LCIPT)[264] and the Community and Renewable Energy Scheme (CARES).[265]

In addition, projects are seeking investment from alternative sources such as private investment companies[266] and crowdfunding.[267] EU funding has been the main source of finance for the two EGS projects based in Cornwall who secured investments of £9.9 million[268] (Eden Geothermal Project) and up to £10.6 million[269] (United Downs Deep Geothermal Power project) from the European Regional Development Fund (ERDF) as part of European Structural and Investment Funding. [270]

5.2 Regulatory framework

Streamlining the regulatory process

Regulation of geothermal schemes is determined by the devolved administrations in the UK, but none of the four nations has bespoke planning rules, environmental regulation or licensing systems that are specific for the planning and operation of geothermal schemes. Instead, geothermal developments are covered by existing regulation, which were initially developed with objectives other than geothermal energy production:

- Planning of geothermal energy schemes is determined by local planning authorities (LPA). Typically, planning consent is required for the development of large GSHP systems and for deep geothermal projects, in some cases including an Environmental Impact Assessment (EIA). Cornwall County Council appears to be the only Local Authority which has developed a policy for geothermal energy installations.[271]
- Environmental regulations applied to geothermal systems are based around licensing of water abstraction and environmental permits for discharging water to the environment determined by the respective environmental regulators.
- For deep geothermal developments, a number of other statutory notices have to be observed relating to the Infrastructure Act 2015[272] and Health and Safety regulations.[273–275]

While regarded by the regulators and many in industry as a functional system, some in industry have expressed concerns that aspects of the regulation for deep geothermal developments (initially developed for hydrocarbon exploration) are "over-engineered" and "unfit for purpose" in the UK geothermal context, adding time and costs to the project. In addition, the multi-agency set-up makes the approval process complicated and time-consuming which is seen as a barrier to deployment by some in the industry who favour a single, bespoke geothermal regulator.[179] Consensus among the industry is that streamlining the regulatory process could promote and facilitate wider uptake of geothermal technologies.[179]

Licensing and permitting

In England and Wales, GSHP systems that utilise groundwater (open-loop systems) are subject to groundwater licensing[141] and environmental permitting[142] regulations issued by the environmental regulator. Some larger schemes (open-loop and closed-loop) may also require planning permission.

Mine energy schemes also need to obtain a mine water heat recovery access agreement from the Coal Authority.

Currently under review (for England & Wales) by the regulator, water abstraction licensing is expected to move into the Environmental Permitting Regulation framework in 2023.[276] While this is likely to simplify the application process for GSHPs, some in industry remain concerned that regulations and planning guidance for GSHPs are not sufficiently clearly defined. They have found that interpretation and application of regulations can vary markedly between different regional offices.

Industry is also concerned about the long timeframes required to obtain the necessary permissions from the regulator, which can take 6–18 months for the pre-application consent(s) and another 9–12 months for the licences and permits. In addition, the Environment Agency is currently reviewing its water resource charges,[277] including the application charges applicable to open-loop GSHPs. While there is consensus that a fee increase is overdue, the proposed change from a fee of £135 for all schemes to a charge of potentially up to £18,308 for large schemes in areas of limited water availability is regarded by the industry as prohibitive to the growth of open-loop GSHPs.

In Scotland, groundwater use by GSHPs is regulated under CAR General Binding Rules (GBR),[278] meaning that no licences or permits are required as long as the scheme meets the conditions of the GBR. Closed-loop GSHP are not regulated, except in Scotland where they are subject to CAR General Binding Rules.[278]

In the UK, geothermal energy is not recognised as a natural resource. As a result, there are no clear rules defining ownership, regulation or management of the geothermal resource.

The Environment Agency has recently (December 2021) consulted on amendments to the Environmental Permitting (England and Wales) Regulations 2016[279] to implement a similar framework in England for closed-loop schemes. The amended regulations would include a requirement for closed-loop GSHPs to comply with GSHPA standards under the General Binding Rules (GBR). The EA is currently considering a response to the consultation.

Managing the heat resource

In the UK, geothermal energy (or heat) is not recognised as a natural resource.[280] As a result, there are no clear rules defining ownership, regulation or management of the geothermal resource.[280] This means that there is currently no regime or regulatory mechanism (like a licensing regime) in the UK for balancing the interests of different users of a particular heat reserve or preventing unsustainable extraction of heat.

Connecting demand and supply and using the ground as buffer for inter-seasonal heat storage and recovery will require some level of management of the heat resource at a systems level. The management could be driven through the planning process, for example the designation of heat network zones (see Section 4.2) although legislative changes may still be required to be able to license or manage the geothermal heat resource. At the current level of deployment, interference problems between subsurface heat users are thought to be minimal, although interference between neighbouring GSHPs is known to occur in London.[137] It is acknowledged by the environmental regulator that a review of the regulations around heat may be needed when deployment of geothermal systems increases and the impacts on the subsurface heat resource are better understood.

In many countries, including Germany, France and the Netherlands, geothermal energy is regulated under the country's mining law and/or the (ground)water law depending on the depth of the resource and whether it involves abstraction of water.[281] The depth at which different regulations are applied varies between the different countries from 100 m in Germany to 500 m in the Netherlands. Uncertainty around ownership of heat and the lack of a licensing regime in the UK is regarded by the industry as a potential barrier for deep geothermal investors and developers.[282]

Land access rights

Regulations for heat networks also differ across the devolved nations. In England and Wales, heat network developers currently do not have the statutory right to access private land for construction or maintenance purposes. Instead, they must negotiate these arrangements on a voluntary basis which can slow down project development or increase project costs. BEIS is currently preparing legislation to address these challenges, including access rights[283] and the regulation of heat networks.[284] It is expected that this legislation will be introduced in 2024/25. Heat networks in Scotland have land access rights similar to other utilities – as defined by the Heat Networks (Scotland) Act 2021.[197]

Induced seismicity

Management of seismic risks from geothermal schemes is part of local planning. There are currently no specific guidelines on the control or definition of acceptable levels of induced seismic ground-shaking for geothermal. The UDDGP and Eden Geothermal projects use a threshold system for controlling and mitigating induced seismicity at their sites.[170,285] The thresholds are based on existing British Standards (BS 6472-2:2008) and Cornwall Council's planning guidelines for blasting, quarrying and mining activity. Rather than measuring the local magnitude of an induced event,[286] the system uses ground motion measurements (or peak ground velocity - PGV) as an indicator for risk of structural damage to buildings from injection-induced seismic events. Magnitude is a measure of the size of the earthquake source. It is the same number no matter how far away the source is from the observer (or receptor) and what the shaking feels like at the surface. PGV is a measure of the ground vibrations (shaking) at the surface and is more directly linked to risk of causing damage to buildings and structures. A PGV of 2 mm/s is considered by British Standard 6472-2:2008 as the "magnitude of vibration below which the probability of adverse comment is low" and is also widely quoted in the literature as the approximate threshold below which vibrations are unlikely to be felt or heard. For comparison, a PGV of 8.5 mm/s is used by Cornwall Council as the maximum permitted level of vibration from blasting operations during working hours. The Eden Geothermal project uses 0.5 mm/s as a PGV threshold during well testing. If exceeded, as on 9 March 2022, operations are halted, the event investigated, and the well testing programme reviewed to minimise the likelihood of inducing another event that could be felt.[174] PGV criteria are increasingly used by EGS for that purpose.[287,288] There is some concern that when used alone, this approach does not consider the impact of nuisance seismicity. This refers to induced seismic events that do not cause structural damage but that can still be felt by residents at some distance from the operational site. In contrast to mining and geothermal, induced seismicity for shale gas operations is regulated via a national 'traffic light system'.[289] The thresholds for seismicity are currently being reconsidered as part of a review commissioned by the government to advise on the latest scientific evidence around shale gas extraction.[290]

6 Innovation and development of additional value streams

6.1 Improving drilling and extraction technologies

Drilling and testing of deep geothermal wells makes up around 65% of the overall costs of a typical deep geothermal (heating) project (Figure 13).[178] Innovations to reduce drilling costs is a priority for developers and investors to make deep geothermal resources more accessible and heat or power production from depths more than 4–5 km more cost-efficient. With improved and cheaper drilling and extraction technologies more of the currently inaccessible resource (total available subsurface commodity) will become available, allowing them to be reclassified as a reserve (resource that can be extracted at a profit). Innovative designs like the Eavor-Loop™, for example, present a new generation of Advanced Geothermal Systems (AGS) that has potential to make geothermal heat and power accessible everywhere irrespective of geology. The Eavor-Loop™ is a buried-pipe system which acts as a large subsurface heat collector. It consists of two vertical wells (several kilometres deep) which are connected by many horizontal multilateral boreholes (several kilometres long). Completing the first prototype power plant in Canada in 2020[291], the technology needs to be tested in a range of other settings to demonstrate environmental viability, cost effectiveness, scalability, and the ability to provide reliable baseload supplies of heat and electricity.

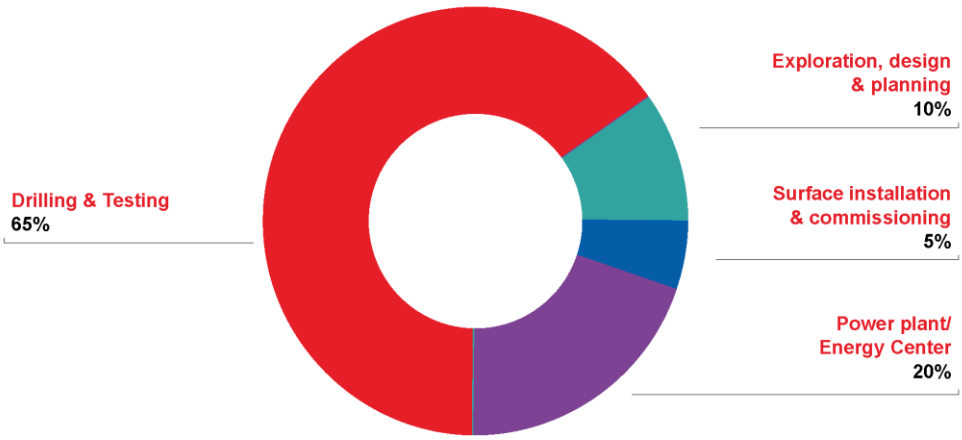

Figure 13: Cost for a typical geothermal heating project (Source: ARUP)

Re-using abandoned hydrocarbon wells for the production of geothermal heat and electricity could reduce costs of geothermal projects by more than 40%.[76] Apart from economic and technical challenges, a number of regulative changes[292] and legal challenges need to be addressed, including the relationship with the decommissioning regime and liability issues.[293] Until

March 2022 , the UK regulator (the North Sea Transition Authority NSTA, formerly the Oil and Gas Authority) required that boreholes are abandoned (capped) within a certain time after hydrocarbon exploration or production ceases, preventing reuse of hydrocarbon wells for geothermal purposes in the UK. On 31 March 2022, the NSTA temporarily suspended the decommissioning requirement for some wells to allow operators to evaluate reuse options.[294]

6.2 Creating additional value streams

Geothermal energy can deliver multiple benefits. At the Eden project in the Cornwall, the geothermal plant will provide heat and electricity for tourism and greenhouses while also supplying neighbouring industries.[295] In the Netherlands, the horticulture industry has been a strong driver for the development of deep geothermal heating projects. Geothermal heat clusters like the Koekoekspolder geothermal project[296] have reduced natural gas consumption of its horticultural companies by 70% to 90%, saving more than 76 tons of carbon dioxide since realisation of the project in 2012.

Geothermal fluids can also contain valuable metals such as lithium - an important raw material in battery production.[297] Lithium is found in the geothermal waters in Cornwall and Weardale.[59,298–300] Pilot projects in Cornwall,[301] Germany,[302,303] France[304] and the US[305] are testing different methods for the extraction of lithium from geothermal brines. Co-production of lithium and geothermal energy could provide an additional value stream,[306,307] improving the business model for geothermal energy at the same time as reducing the environmental and carbon footprint of lithium.[299]

6.3 Innovative business models

In addition to technical innovation, innovation in business models is regarded as an important step for upscaling geothermal deployment, particularly in the GSHP sector. New service and ownership models are starting to emerge, including provision of ‘heat as a service’, [308] where customers pay for an energy service without having to make any upfront capital investment, or ‘split ownership’ of shared ground-loops,[309] where external investors take separate ownership of the ground array assets. The latter model is the same as the gas infrastructure being owned by entities quite distinct from the householder. The proposed heat network zoning approach (see Section 4.2) could be a potential catalyst for accelerating business model innovation, for example by defining ground-loops as an infrastructure asset within the wider heat network system. Other business models include energy service agreements (ESA) where an energy services company (ESCO) delivers ‘energy/heat as a service’ to a customer.[310] The advantage of such models is that the ESCO finances the scheme by borrowing against future utility payments, with no upfront capital investment required from the individual customers.

Glossary of terms

Air source heat pump (ASHP): see heat pump.

Amagmatic geothermal system: systems in which molten rock is lacking, but heat flow and geothermal gradient are enhanced due to stretching of the Earth's crust.

Ambient ground-loop: see shared ground-loop.

Aquifer: underground layers of water-bearing, permeable rocks that contain and transmit groundwater and from which groundwater can be extracted.

Baseload: the minimum amount of electrical power needed to be supplied to the national electricity grid at any given time.

Borehole heat exchanger: closed pipe loops installed in boreholes in the ground through which a heat-carrier fluid is circulated to collect heat or cold from the ground.

Boreholes: deep, narrow holes made in the ground, often to locate water or oil.

Closed-loop GSHP system: systems that extract heat or cold from the ground by circulating a heat carrier fluid around an array of closed pipe loops (borehole heat exchanger). These systems are typically installed vertically or horizontally at depth of more than 500 m.

Conduction: the process by which heat is directly transmitted from one material or substance to another as a result of a difference in temperature.

Convection: the movement within a fluid caused by the tendency of hotter (less dense) material to rise and colder (denser) material to sink under the influence of gravity, which consequently results in circulation and transfer of heat.

Deep geothermal: term used widely to refer to systems at a depth of more than 500 m below the surface. In this document, the term is used to refer to geothermal systems that are sufficiently hot for direct-use heating applications (without requiring a heat pump) or power generation.

Direct-use geothermal: a system that is hot enough for geothermal heat to be used directly (for example for district heating) without requiring an electrical heat pump.

District Heating: communal heating systems that deliver heated water to a large number of homes and buildings via a heat network.

Earth's crust: uppermost layer of the Earth that is made of solid rocks and minerals. It varies in thickness from 5–10 kilometres beneath oceans to up to 70 km beneath continents.

Earth's mantle: the layer beneath the Earth's crust. It is mostly solid rocks and minerals but includes some areas of semi-solid molten rock (magma).

Enhanced geothermal systems: unconventional geothermal systems for the production of heat or electricity. They are created where there is hot rock but insufficient natural fluid and/or permeability within the system to transport this heat to the surface.

Geothermal brine: the hot, saline solution pumped from deep geothermal systems. It has circulated through deep sedimentary basins and crustal rocks and is enriched in minerals and element leached from those rocks.

Geothermal doublet: a geothermal system consisting of two boreholes - one for abstracting the warm/hot water from permeable, water-filled rocks and one for re-injecting the cooled water (after heat extraction) back into the geothermal aquifer.

Geothermal reservoirs: underground zones of porous or fractured rock that contain hot water and/or steam. They can be naturally occurring or human-made.

Gigawatt (GW): a unit of power equal to one billion (10^9) watts.

Gigawatt-hours (GWh): a unit of energy equal to one billion (10^9) watt-hours.

Grams of carbon dioxide (equivalent) per kilowatt-hour ($gCO_2(eq)/kWh$): a measure of carbon intensity for a technology or power system (PN 383).

Ground swelling: the volume increase that occurs as a result of changes in the moisture content or mineralogy of the ground (soils or rocks). It can cause heave or lifting of structures. The opposite process is shrinkage which can cause settlement or subsidence.

Ground source heat pump (GSHP): see heat pump.

Groundwater: water that exists in pores and fractures in the rocks and soils beneath the land surface where it forms saturated zones (aquifers).

Heat exchanger: a device for transferring heat from one fluid to another, or for transferring heat to or from the ground.

Heat network: a distribution system of insulated pipes that takes heat from a central source and delivers it to domestic or non-domestic buildings.

Hot sedimentary aquifers: see hydrothermal systems.

Heat pump: a device that transfers and 'upgrades' heat from a colder space to a warmer space using mechanical energy. There are three main types of heat pump: ground source, air source and water source. The name of each one describes where the appliance takes its heat from. A heat pump can also function as an air conditioner to provide space cooling.

Hybrid heat pump: systems that use a combination of renewable energy and fossil fuels for space heating. One component of the system is the heat pump (ASHP or GSHP), and the other is a traditional gas, oil or LPG heating component.

Hydrothermal systems (also referred to as 'hot sedimentary aquifers'): geothermal systems that contain fluid, heat and permeability in a naturally occurring geological formation or sedimentary basin for the production of heat or electricity.

Igneous (or magmatic) rocks: rocks formed through the cooling and hardening of molten rock (magma). A body of magma that cools and hardens below the surface is called an **igneous intrusion**.

Induced seismicity: typically minor earthquakes and tremors that are caused by human activities that alters the local stress field. Most induced seismicity is of low magnitude.

Joule (J): the standard unit of energy. One joule is equivalent to the energy released as heat when an electrical current of one ampere passes through a resistance of one ohm for one second. One joule equals one watt-second or 0.00028 watt-hours.

Kilowatt (kW): a unit of power equal to one thousand (10^3) watts.

Kilowatt-hour (kWh): a unit of energy equal to one thousand (10^3) watt-hours.

Magmatic rocks: see igneous rocks.

Metamorphic rocks: rocks formed when an existing body of rock is subjected to high temperatures and pressures which cause considerable changes to the mineral composition and texture of the original.

Magmatic geothermal system: systems in which the dominant source of heat is a large deeply buried reservoir of molten rock (magma).

Megajoules (MJ): a unit of energy equal to one million (10^6) joules.

Megawatt (MW): a unit of power equal to one million (10^6) watts.

Meteoric water: water that is directly and indirectly derived from precipitation (snow and rain), including water from lakes, rivers and ice melts.

Microgeneration Certification Scheme (MCS): a standards body that certifies, quality assures and provides consumer protection for microgeneration installations and installers. MCS certifies installations, including GSHPs, and oversees the development of standards by technical working groups, including members from industry.

Open-loop GSHP system: a geothermal system that typically pumps warm groundwater directly from an aquifer or flooded mine system via a production borehole and, after heat extraction, returns the cooled water to the system via an injection borehole (see also geothermal doublet).

Permeability: a measure of whether and how fast water can flow through a rock.

Petajoule (PJ): a unit of energy equal to one quadrillion (10^{15}) joules.

Radiogenic: heat produced within the rocks by the natural radioactive decay of isotopes of uranium, thorium and potassium.

Reserves: that part of a resource that has been discovered, has a known size, and can be extracted at profit.

Resource: the amount of a geologic commodity that exists in discovered and undiscovered deposits or systems.

Sedimentary basins: low areas in the Earth's crust, of tectonic origin, in which thick deposits of sediments accumulate over geological time periods.

Seismicity: see induced seismicity.

Shallow geothermal: term used widely to refer to systems at depths of less than 500 m below surface. In this document, the term is used to refer to systems that use ground-source heat pumps.

Shared ground-loop: a district heating network where at least two or more properties have an individual heat pump connected to a communal borehole heat exchanger ground-loop.

Subsidence: the gradual caving in or sinking of an area of land, for example as a result of shrinkage (see ground swelling).

Subsurface Urban heat island (SUHI): the raised ground(water) temperatures beneath urban areas (resulting from urban land use change and anthropogenic heat losses) relative to the rural background.

Terawatt (TW): a unit of power equal to one trillion (10^{12}) watts.

Terawatt hours (TWh): a unit of energy equal to one trillion (10^{12}) watt-hours.

Underground thermal energy storage (UTES): system in which hot water is pumped into underground boreholes, aquifers or caverns for the temporary storage of thermal energy.

Water Source Heat Pump (WSHP): see heat pump.

Watt (W): a unit of power - the rate at which energy is transferred or converted.

Watt-hour (Wh): a unit of energy equivalent to using one watt of electricity for one hour. One watt-hour is equal to 3,600 joules.

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