Evidence report supporting the deep geothermal energy white paper: The case for deep geothermal energy - unlocking investment at scale in the UK

Decarbonisation and Resource Management Programme
Open Report OR/23/032

BRITISH GEOLOGICAL SURVEY

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C Abesser; A Gonzalez Quiros; J Boddy

Contributors

D Jones; A Monaghan; R Raine; S Johal; S Price; M Free

Report; keywords geothermal resources, opportunities, policy, regulation, Europe, supply chain, stakeholders, policy analysis.

Front cover

Drill rig at the Eden Geothermal Project, Cornwall, UK. (BGS © UKRI 2023).

Bibliographical reference

ABESSER, C, GONZALEZ QUIROS, A; BODDY, J 2023. Evidence report supporting the deep geothermal energy white paper: The case for deep geothermal energy - unlocking investment at scale in the UK. *British Geological Survey Open Report*, OR/23/032. 134pp.

Keyworth, Nottingham British Geological Survey 2023

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British Geological Survey offices

Nicker Hill, Keyworth,
Nottingham NG12 5GG
Tel 0115 936 3100

BGS Central Enquiries Desk
Tel 0115 936 3143
email enquiries@bgs.ac.uk

BGS Sales
Tel 0115 936 3241
email sales@bgs.ac.uk

The Lyell Centre, Research Avenue South,
Edinburgh EH14 4AP
Tel 0131 667 1000

Natural History Museum, Cromwell Road,
London SW7 5BD
Tel 020 7589 4090
Tel 020 7942 5344/45
email bgslondonstaff@bgs.ac.uk

Cardiff University, Main Building, Park Place,
Cardiff CF10 3AT
Tel 029 2167 4280

Maclean Building, Crowmarsh Gifford,
Wallingford OX10 8BB
Tel 01491 838800

Geological Survey of Northern Ireland, Department for the Economy, Dundonald House, Upper Newtownards Road, Ballymiscaw, Belfast, BT4 3SB
Tel 0289 038 8462
www2.bgs.ac.uk/gsni/

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon SN2 1EU
Tel 01793 411500
Fax 01793 411501
www.nerc.ac.uk

UK Research and Innovation, Polaris House, Swindon SN2 1FL
Tel 01793 444000
www.ukri.org

Website www.bgs.ac.uk
Shop online at shop.bgs.ac.uk

Foreword

This report provides the evidence base, including contextual information and data, that underpins the deep geothermal energy white paper: “*The case for deep geothermal energy – unlocking investment at scale in the UK. A deep geothermal energy white paper*”, available at

https://www.northeastlep.co.uk/updates/white-paper-calls-for-acceleration-of-geothermal-energy-projects-in-the-uk/

The white paper provides an evidence-based assessment and ‘case making’ document to help accelerate the development and deployment of deep geothermal energy projects. It was commissioned by the North East Local Enterprise Partnership (LEP), funded by the Department for Energy Security and Net Zero (DESNZ) and the North East and Yorkshire Net Zero Hub in 2022, and led by the British Geological Survey and Arup. The commission follows and is intended to complement the white paper on Mine Energy which was led and procured by the North East LEP during 2020 and 2021, on behalf of the UK Mine Energy Taskforce.

This evidence report is written by the British Geological Survey (BGS) with funding from UK Research and Innovation (UKRI), delivered through The Natural Environment Research Council (NERC), that supports BGS’ public science role. It is a supplementary output to the work commissioned by North East LEP, intended to present the evidence base and contextual knowledge that underpins the white paper.

The report includes the evidence and outputs from the work commissioned by North East LEP, including the data collated as part of the commissioned (Appendices 1-5), key findings and recommendations (Chapters 4-6), a suite of maps illustrating potential geothermal resources and opportunities in the UK (Figures 11-16, 18) and an infographic (roadmap) setting out the project flow and different project development stages of a deep geothermal energy project (Appendix 4). Figures that form part of the commission are identified as © North East LEP in the report.

The evidence report includes more detailed information and data on UK geothermal prospects and opportunities, including data and analyses from BGS studies that did not form part of the North East LEP commission (identified as BGS © UKRI, 2023). In addition to data, the report shares the authors’ wider contextual knowledge that underpins the white paper and provides more detailed discussions of the evidence and findings within the context of international geothermal developments and experiences. It also provides descriptions of the methodologies adopted in developing the white paper, including the stakeholder engagement, and how evidence was collected, analysed and translated into a set of recommendations.

Acknowledgements

Project team for white paper

Dr Corinna Abesser	British Geological Survey
Dr Andres Gonzalez Quiros	British Geological Survey
Darren Jones	British Geological Survey
Dr Alison Monaghan	British Geological Survey
Robert Raine	Geological Survey of Northern Ireland
Jason Boddy	Arup
Simran Johal	Arup
Dr Simon Price	Arup
Dr Matthew Free	Arup
Dr Bobo Ng[1]	North East Local Enterprise Partnership

Project Steering Group

Caroline Caroll	Cornwall and Isles of Scilly Local Enterprise Partnership
Andrew Clark	North East Local Enterprise Partnership
Neil Davis	Department for Energy Security and Net Zero
Gus Grand	Eden Geothermal Ltd
Professor Jon Gluyas[1]	Durham Energy Institute / GeoEnergy Durham
Dr Melanie Jans-Singh[1]	Department for Energy Security and Net Zero
Sanjeev Kumar	European Geothermal Energy Council
Eloise Travis	Cornwall Council
Timme van Melle	Energie Beheer Nederland

Consultees[2]

Brian Appleby	Ministry of Defence
Richard Baker	North East Local Enterprise Partnership
Andrew Briggs	City of Stoke-on-Trent
Hester Claridge	TownRock Energy
Dr Marie Cowan	Geological Survey of Northern Ireland
Dr Andrew Cripps	Triple Point Heat Networks Investment Management
Dr Helen Doran	Project InnerSpace
Hazel Farndale	Geothermal Engineering Ltd
Dr Mark Ireland	Newcastle University
Professor Christopher Jackson	Jacobs UK Ltd
Dr Ryan Law	Geothermal Engineering Ltd
Peter Ledingham	GeoScience Ltd

[1] Also acted as technical reviewer of the report.
[2] The list includes individuals and companies who attended the workshop or were interviewed and who gave their permission to be named. Their inclusion should not be taken as evidence of endorsement.

Cornish Lithium Plc

David Maddan	The Auckland Project
Kevin J Mallin	Geolorn Ltd
Jason Taylor	Southampton City Council
David Townsend	TownRock Energy
Dr Chris Sladen	Geothermal Energy Advancement Association
Ann-marie Wilkinson	GT Energy

We also wish to acknowledge the contribution of several unnamed contributors, including unnamed participants of the workshop and the 58 anonymous participants of the online survey.

Commisioned by

North East Local Enterprise Partnership

Funded by

Department for Energy Security and Net Zero

North East & Yorkshire Net Zero Hub

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INTRODUCTION

Under the amended UK Climate Change Act, a reduction in the emission of greenhouse gases of at least 80% from 1990 levels is necessary to reach net-zero targets by 2050. The sixth carbon budget for the period 2033–2037 requires a reduction of at least 63% from 1990 levels. While the UK has made good progress in decarbonising electricity, the decarbonisation of heating and cooling remains a challenge. Buildings, for example, were the UK's second largest source of emissions in 2021 (after surface transport), producing 20% of all UK emissions.[3]

Geothermal energy, the energy generated and stored in the form of heat in rocks, groundwater and soils, can provide a low-carbon source for heating, cooling and power generation. Deep geothermal resources, typically at depths of more than 500 m below the ground surface and temperatures between 50 and 200°C, are suitable for multiple uses, including direct use for space heating, cooling (using absorption chiller technology), horticulture, a variety of industrial processes or power generation.

A 'UK Deep Geothermal Energy White Paper' was commissioned by the North East Local Enterprise Partnership (LEP) and funded by the Department for Energy Security and Net Zero (DESNZ) and the North East and Yorkshire Net Zero Hub in 2022. It aims to provide an evidence-based assessment and 'case making' document to help accelerate the development and deployment of deep geothermal energy projects in the UK. This report provides the underpinning evidence, background and data for the white paper.

It describes stakeholder input which was collected through a range of engagement events, including a review of existing stakeholder evidence (including 31 submissions to a parliamentary inquiry on geothermal technology undertaken by the Environmental Audit Committee in 2022), a virtual stakeholder workshop (34 participants), an online stakeholder survey (59 respondents) and stakeholder interviews (7). Stakeholders that have participated in the engagement for this report include representatives from the geothermal industry (developers, consultants, drillers, service providers), regulators, the finance sector and academia.

GEOTHERMAL LANDSCAPE

In countries like France, Germany, Belgium and the Netherlands, which have a similar geology to the UK, deep geothermal energy has been shown to offer environmental, economic and technical advantages, including reductions in greenhouse gas emissions, economic impetus and job generation. Operational projects in the Netherlands have saved 342,000 tonnes of CO_2 compared to using gas in 2021. In Germany, the geothermal industry has generated €16.7 billion and created 35,900 jobs since 2000. These applications have also demonstrated the feasibility of using deep geothermal sources for large-scale district heating and cooling as well as 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.

Capital expenditure (CAPEX) makes up 87% of the fixed cost and 37% of the overall costs of a geothermal project with a 30-year lifespan. The cost of drilling, well completion and testing remain the primary driver of high geothermal project costs. Pilot wells tend to be the most expensive but drilling costs are seen to reduce over time for a given area and/or geology. As more wells are drilled, the experiences gained allow drilling to be completed faster, resulting in cost reductions. In the SW Molasse Basin of Germany, for example, the reduction in drilling time directly translated into a reduction in average drilling cost (excluding site preparation and well testing) from €1.4 to €1.1 million per drilled km.

The average weighted levelised cost of heating (LCOH) for European geothermal projects (excluding Iceland) is around 37 €/MWh but there is some variation between and within countries. The variations are due to factors like project size, well numbers and depths, but also ground-level temperature. For recent projects, higher costs also reflect a general rise in drilling

[3] Climate Change committee (2022) Progress in reducing emissions. 2022 Report to Parliament

cost over the past few years. As for heating, the levelised cost of electricity (LCOE) for geothermal power projects is site sensitive and shows large variations between and within countries. It is also influenced by the type of installed power plant, which in turn, is dependent on the available geothermal resource. For France, a value of 160 €/MWh is reported for a 3 MW Enhanced Geothermal System with two boreholes.

Geothermal energy is widely used in district heating across Europe with networks ranging in capacity from < 1 to 50 MW_{th}. Although there is a high capital expenditure, the fixed operation and maintenance costs are in line with other renewable energies, and variable costs are low.

Several countries and regional governments have included geothermal energy in their energy planning and Net Zero strategies and have commissioned studies to identify the geothermal potential of the country for heat and/or power production or geothermal district heating (e.g., the state of Bavaria, Germany and the Republic of Ireland). A few countries have defined specific strategies and targets for developing their geothermal sector. The Dutch Government, for example, has defined a clear commitment to developing geothermal energy in the Netherlands to support its move away from gas.

Geothermal energy is recognised as a natural resource in most of the countries reviewed in this report. Where existing legal definitions did not include geothermal energy, legislation was amended, or new regulation passed that defines geothermal heat as a natural resource with clear rules of ownership, regulations, and licensing arrangements. Licensing arrangements typically involve two licences, one for exploration and one for exploitation (production).

Experiences from the reviewed countries suggest that availability of various direct and indirect support measures like competitive subsidies, sustained, long-term government support, insurance schemes as well as data availability through open-access tools and data sharing obligations have been instrumental in building a geothermal sector in these countries.

GEOTHERMAL POTENTIAL IN THE UK

The UK’s onshore deep geothermal potential occurs in two main geological settings: deep sedimentary basins and radiogenic granites.

Deep sedimentary basins typically contain deeply buried limestones and sandstones. Where water circulates through these deep rocks (at 1-3 km) they form hot sedimentary aquifers (HSA) or fractured sedimentary aquifers (a sub-type of HSA). Most of the UK’s deep geothermal potential exists or is contained within deep sedimentary basins which occur in many parts of Great Britain and Northern Ireland. Temperatures within the onshore basins are estimated to lie in the range of 40–60°C but may reach 100°C or more in some deeper parts. This temperature range makes these systems most suited for geothermal heating applications such as district heat networks, horticulture and industry. HSA are also present offshore in deep sedimentary basins of the UK Continental Shelf. These are not considered in this study.

Granites, typically, are tight rocks, that is, they have little ability to store or transport water, except where the rocks are naturally faulted or fractured. Granites can contain a higher proportion of radioactive elements than other rock types. Where heat from the decay of these elements accumulates within the rocks, these radiogenic granites form so called “Hot Dry Rock” (HDR) systems and are a target for geothermal energy exploitation. Some granites found in Cornwall, the North of England, Scotland and Northern Ireland have been identified as potential geothermal targets. Temperatures within these rocks are estimated to reach up to 200°C at 5 km depth – sufficient for geothermal power generation. Recent drilling to about 5 km depth in Cornwall has confirmed that such temperatures can be achieved in the granites of Southwest England. Drilling to shallower depths into some granites in Northern England has confirmed an above-average temperature gradient within these rocks. The geothermal potential of the granites in other areas is subject to higher uncertainty due to a lack of data. With current drilling technologies and typical funding models, the radiogenic granites are considered the only systems in the UK that potentially have sufficient enthalpy for geothermal power generation.

Several deep geothermal projects are in development in different parts of the UK. The most advanced are the two Enhanced Geothermal System (EGS) projects in Cornwall. One project has started supplying heat to the Eden Project biomes and offices. The other located at United Downs is expected to enter the production stage later in 2023, supplying geothermal heat and power. The 1.7 km-deep well in Southampton, which started operation in the 1980s, was the first operational deep geothermal well in the UK but it is currently not in operation. Several new deep geothermal projects have recently been granted planning permission.

OPPORTUNITIES FOR DEEP GEOTHERMAL IN THE UK

Stakeholder views, collected during this study and as part of a recent inquiry conducted by the Environmental Audit Committee, strongly agree that there is potential for developing deep geothermal in the UK, especially for space heating, industrial heating, and agriculture/ horticulture heat use. There is consensus that geothermal development should focus on exploiting the resources at moderate depths (1-3 km) for direct-use heating and thermal energy storage. This is because commercially achievable enthalpies in the UK's sedimentary basins (which make up most of the available geothermal potential) are not expected to be high enough for power generation within economically drillable depths (currently at 5-6 km). Furthermore, geothermal heating technologies are seen to be more readily deployable than technology for power generation (i.e., they do not require construction of a power plant) and generally entail lower risks. It is recognised, however, that in some areas of the UK, such as Cornwall, special geological conditions exist which could make power generation economically viable. However, the focus of geothermal developments in the UK is seen to be weighted towards heating applications.

Beside decarbonisation benefits and provision of low-carbon heat, stakeholders also identified additional benefits of geothermal energy including energy security, just energy transition opportunities, co-production of critical minerals and the potential for reuse of existing energy infrastructure (e.g., oil and gas wells).

Net Zero: Decarbonisation benefits

Geothermal energy is available across the UK. It is most economically feasible to exploit it for geothermal heating applications, such as district heating or horticulture, given the achievable temperatures within economical drilling depths. In some places, temperatures are hot enough and production rates can be sufficient for power generation.

It is estimated that individual projects in the UK could deliver savings of between 2,400 tonnes and 14,000 tonnes of CO_2 equivalent per year (compared with natural gas) for geothermal heating and power operations, totalling savings of 72,000 tonnes (geothermal heating project) and 700,000 tonnes (geothermal power project) of CO_2 equivalent over their estimated thirty-year and fifty-year operational lifetime, respectively.

With one of the lowest carbon footprints compared with other space and water heating technologies (such as gas or coal), the use of geothermal energy for district heating networks could achieve a considerable reduction of greenhouse gas emissions in the UK. The city of Munich (Germany), for example, supplies around 50,000 homes with geothermal heating, saving about 75,400 tonnes of CO_2 per year compared with gas.

The public sector estate is one of the main emitters of greenhouse gases (for heating) in the UK, with large buildings (for example hospitals, prisons, army barracks) having predictable and continuous heating requirements. Such buildings provide ideal anchor loads for geothermal projects as well as for district heating networks and are attractive to geothermal developers because of the potential for obtaining reliable, long-term heat purchase agreements. Retrofitting a geothermal heat source to existing buildings may require an upgrade to existing heat networks or building of a new one. Where the geothermal resource has not been proven, the achievable heat loads will remain uncertain until a well has been drilled. This uncertainty may prevent uptake of geothermal heating by the public sector.

Geothermal technologies can be combined to optimise costs or adopt to unforeseen geological and temperature conditions (e.g. temperatures from a moderately deep well can be boosted with a heat pump). Net efficiency and economic feasibility of geothermal projects can be enhanced through cascade use (i.e. consecutive use of the produced steam or hot water for more than one application, typically with decreasing temperature requirements), delivering cost benefits to a range of users by conditions with different requirements.

Energy Security

Geothermal energy provides a decentralised energy source that is available over a wide geographical area of the UK, 24 hours per day and independent of the weather. A well-developed geothermal sector can produce geothermal heating (and some electricity) with little reliance on external factors like skills and supply chains. This could significantly reduce the UK's reliance on third country suppliers of gas, thereby contributing to increased energy security. Furthermore, geothermal energy does not require rare or critical minerals for construction of its infrastructure.

Economic Benefits: Green Growth and Energy Transition

As well as emissions savings, geothermal projects can provide economic stimulus and contribute to job generation. The United Downs project in the UK is estimated to have contributed £1.5 million to the local economy in Cornwall across a range of sectors, including food and hospitality, groundworks engineering, security services, health and safety supplies and monitoring services.

The development of deep geothermal energy in the UK (onshore and offshore) could provide a unique opportunity to the oil and gas sector to transition its jobs, skills, knowledge and economic activity to a low-carbon technology, supporting the government's North Sea transition agenda. It also offers the possibility of reutilising some of the infrastructure, for example through repurposing of oil and gas wells for geothermal production.

Social Benefits: Levelling Up

Many of the deep geothermal prospects in the UK coincide with areas identified by the UK Community Renewal Fund as the top 100 places in need of economic stimulus. Investment in geothermal projects in these areas could contribute to the UK Government's levelling up agenda, through addressing energy poverty and creating green jobs.

Use of geothermal energy for heating spas and swimming pools has been reported in many countries to provide considerable social benefit for tens of thousands of people each year, including improved quality of life through availability of affordable recreational facilities for swimming, bathing and therapy, as well as providing some local income through tourism. The now partially geothermally-heated Jubilee Pool in Penzance, for example, reported visitor numbers of over 40,000 people in 2017. It offers a 20% discount to people living in Penzance as well as tailored programmes for up to 180 people per week aimed at improving their health and well-being.

Links to other technologies

The UK has about 2,100 onshore wells that were drilled for oil, gas, unconventional hydrocarbons, coal bed methane or other purposes. A small number of these wells may be suitable for re-use for geothermal purposes provided they have not yet been fully decommissioned and there is a nearby consumer (e.g., horticulture or agriculture use). Re-using abandoned hydrocarbon wells to produce geothermal heat and electricity could reduce costs of geothermal projects because it avoids the high capital costs associated with drilling. Pilot projects are testing different technologies for the repurposing of wells. In addition to outstanding economic and technical challenges, there are several regulative changes and legal challenges that need to be addressed, including the relationship with the decommissioning regime and liability issues. Clearer assignment of responsibilities (e.g., through identifying an authority with responsibility for geothermal energy) and introduction of a geothermal licensing regime would reduce risk and uncertainty to investors and developers planning new projects.

There is increased interest in combining geothermal energy production and Carbon Capture and Storage concepts. These concepts are at various stages of development, ranging from being largely conceptual (i.e., using supercritical CO_2 as a working fluid) to operational pilot plants (carbon fixture in geothermal reservoirs). They have potential to deliver co-benefits and cost reductions to geothermal projects.

Geothermal fluids can contain valuable metals such as lithium: an important raw material in battery production. Lithium is found in the geothermal waters in Cornwall and Weardale. Pilot projects are testing different methods for the extraction of lithium from geothermal brines. If proven economical, co-production of lithium and geothermal energy could provide an additional value stream for geothermal energy and contribute to the UK's security of resources, although the overall contribution is likely to be small.

Future technologies

Future technologies will play an important role in unlocking geothermal resources that currently cannot be exploited cost effectively. Technology developments, in particular improvements in drilling technologies, and associated reductions in costs are expected to make more of the deep, hot subsurface accessible for exploitation.

Several innovative technologies are being developed that have potential to unlock part of the currently inaccessible geothermal resource, including advanced geothermal systems (AGS), superhot rock systems (SHR), ultra-deep drilling technologies as well as heating technology innovation (e.g. high temperature heat pumps). As new technologies become available, the geothermal energy resource that is economically exploitable is likely to expand in many areas of the UK.

UK STAKEHOLDER VIEWS OF CHALLENGES AND CONSTRAINTS

Stakeholder evidence from engagement during this study as well as from existing research has identified several challenges for geothermal energy in the UK.

Project Costs and Risks

Geothermal projects have high capital expenditure (CAPEX), most of which is spent on drilling and materials. In addition, there is geological and financial uncertainty over the subsurface conditions and volume of revenue that will be delivered. High upfront costs and drilling risks are considered a main barrier to wider uptake of geothermal energy in the UK as they make it difficult to obtain project finance under current technology awareness and market conditions. Projects currently need financial support to improve their commercial viability and reduce risks to developers and investors.

Risk of project failure is higher in unexplored areas and at the start of new projects because there is limited information on the deep geology. The risk reduces after the drilling of the first well which decreases the uncertainty regarding the temperature and flow rate. These parameters define the capacity of the geothermal project, and therefore the revenue. Stakeholders have identified a need for risk-sharing mechanisms for geothermal projects like those available in other European countries.

Financial support for geothermal projects and risk sharing measures are particularly important during early stages of market development when investment is seen as high risk because technology experience is limited and achievable returns on investment are unknown.

Technology Awareness

Stakeholders highlight that awareness of geothermal energy technologies varies amongst different public groups and that many policy makers (central government and regulators) and potential end-user or clients (local councils, site and building developers) are less aware of geothermal technology options. The Heat and Buildings Strategy and the Independent Review of Net Zero identify geothermal energy as a potential source for district heating and as an area that needs further research in the UK. The role for geothermal energy in the UK energy transition is currently not defined and there are no targets for developing deep geothermal technologies as part of the UK decarbonisation and net zero efforts. This is seen by many stakeholders as a key barrier for the development of a deep geothermal sector in the UK.

Most respondents (69%) to the online survey perceive public acceptance of geothermal to be positive. However, there is very little direct knowledge on the public perception, knowledge, and acceptance of geothermal technologies in the UK population. A recent study, conducted within the context of the mine water geothermal research site in Glasgow (UK Geoenergy Observatory), highlighted three inter-linked themes that are of most concern to the public with regards to geothermal technologies: risk, accountability, and trust. Many participants in that study felt that they wanted more information about the benefits and risks of each of the technologies, to be involved in the decision-making process and to help them make more informed decisions. There is strong consensus amongst stakeholders consulted for this White Paper that public engagement is an extremely important aspect of geothermal projects, and that ineffective public engagement could create a barrier for the entire industry.

Government Support and Investment

Stakeholders reported that it is difficult to get funding for geothermal projects due to limited availability of financial support mechanisms. As for other renewable technologies, government incentives are important during early stages of market development to build investors' confidence and drive cost reductions. Current deep geothermal developments in Cornwall, for example, were only able to start with initial support from the European Union's European Regional Development Fund (ERDF) and from the local authority. They only received backing from private investors during later project stages once the project risks were better understood. Since the UK's departure from the EU, funding such as ERDF is no longer accessible by UK-based projects.

There is currently no government support available for deep geothermal heat projects, except for public sector organisations or in conjunction with heat networks. Contracts for Difference (CfDs) is the Government's main mechanism for supporting low-carbon electricity generation. Under current conditions, the likelihood of a geothermal bid being successful in a CfD auction is very low because geothermal power competes against more developed technologies such as offshore wind or Advanced Conversion Technologies (ACT) and because there is no guaranteed minimum allocation for geothermal power projects.

Local councils and public sector organisations are seen by stakeholders as key potential users of geothermal energy for decarbonising their estate. However, uptake of the technology by these organisations is currently inhibited by the high capital costs of both, heat networks and geothermal projects. Furthermore, limited data availability and the resulting risks associated with unknown geological conditions make it difficult to justify investment into deep geothermal projects against lower risk options. The Heat Networks Delivery Unit (HNDU) provides support to local authorities in England and Wales through the early stages of heat network development, including for techno-economic feasibility – but does not include drilling costs.

Overall, the support available for geothermal project was seen by most stakeholders as poorer compared to support given to other renewable technologies, such as wind and solar.

Legislative support

Legislative measures like banning installations of fossil fuel fired heating systems in new and retrofitted buildings have recently been introduced in Belgium, Germany, and the Netherlands but are not currently available in the UK. The UK Government has announced plans to introduce a new Future Homes Standard and Future Building Standard in 2025, including a stipulation that new homes must be "zero carbon ready". Stakeholders regard the current absence of such legislative measures as a potential challenge for the wider adoption of low-carbon heating technologies. Until details of the policy have been announced and passed into legislation it will remain unknown to what degree these measures will encourage deep geothermal developments.

Data Availability

Participants have identified a need for improving availability and accessibility to subsurface data to progress the sector, including information about available resources. Data availability and accessibility issues are seen as a barrier by developers and by potential clients/ users, specifically to identifying opportunities and areas for geothermal developments across the UK.

The British Geological Survey has a mandated role to provide geothermal advice and expertise to the UK Government. It is currently undertaking a programme of work to improve the quality and reliability of legacy data sets, such as the 'Geothermal Data Catalogue', and develop tools through which improved data sets can be delivered. In 2023, the North Sea Transition Authority

(NSTA) authorised the release of all well data for onshore hydrocarbon boreholes held by BGS. These are now available free of charge via the BGS Geoindex.

Lack of data and sharing obligations was also seen as a challenge for a potential geothermal regulator who would require such data and information to formulate a regulatory approach and/or make decisions about individual systems.

UK Geothermal supply chain

Although some elements of the supply chain exist in the UK, stakeholders found that these are not coordinated because of the limited number of UK deep geothermal projects. In some areas (e.g, seismic data acquisition), stakeholders reported that the UK supply chain has been reducing for many years with only a minimum level of skills and capacity retained in the UK today. UK service providers highlighted that the existing capacity can be built up, but they need a minimum of two-three consecutive projects and a minimum of two months of work to make re-engagement in geothermal data acquisition worthwhile.

Drilling skills and some equipment are thought to be available and geothermal technologies are sufficiently mature for deployment for geothermal heat and for power generation. However, current projects had to source some specialist equipment and skills (e.g., deep drilling) from outside the UK. The lack of an established and coordinated supply chain is seen by some stakeholders as a barrier to uptake of geothermal systems and is identified as adding time and costs to projects that are currently in development in the UK.

Having a pipeline of projects is regarded as important by stakeholders to help develop skills, generate momentum for the industry and engage the supply chain companies, as well as to encourage investment. To build confidence and re-engage the supply chain, stakeholders proposed visible government geothermal demonstrators at key government infrastructure (e.g. hospitals, government buildings, schools), thereby also contributing to the decarbonisation of the public sector.

Technology

Technology readiness for the drilling and installation of geothermal heat and power projects is considered by stakeholders to be high. However, they remain the most expensive elements of a geothermal project. With standing times for drilling rigs of £40k/day, technology innovation for faster, more efficient drilling and well completion is seen by most stakeholders as a priority for innovation. There are several active projects around the world developing new drilling technologies, including technologies that have potential to disrupt current drilling practice. Other areas where technology innovation is needed include the conversion of oil and gas wells for geothermal uses.

Regulation

Stakeholders highlighted that geothermal energy is not recognised as a natural resource (such as minerals or water) and that this leads to uncertainty in the status, ownership, and regulation of geothermal energy.

Responsibilities for regulation of deep geothermal systems are currently split between different authorities including local planning authorities, environmental regulators and the Health and Safety Executive (for deep drilling). With only a few deep geothermal systems currently in development, the regulatory system has not been fully tested. Environmental impacts were considered low by stakeholders of this and previous studies. Risks associated with geothermal projects are seen to be well-covered by existing regulation, although some stakeholders identified inconsistencies in their application that should be addressed.

Introduction of a licensing system is seen as important by some stakeholders as it offers assurance to investors and a clear route for development. It would also enable regulators to impose conditions on operators relating to community engagement requirements or data sharing commitments. However, it is recognised that a critical mass of projects is needed before licensing is introduced.

BUILDING THE SECTOR: RECOMMENDATIONS

Several recommendations that could support the development of a geothermal sector in the UK were identified in conclusion of this study. A summary of these recommendations is included below for the short-term (< 5 years), medium-term (5-15 years) and long-term (>15 years).

	Short Term	Medium Term	Long Term
1. Reviewing financial support for geothermal energy	Support mechanisms that reflect market maturity		
	Measures to encourage technology uptake (e.g. Feed-in Tariff, Contract for Difference)	Measures for scaling up the deployment (e.g. rolling funds)	Measures to encourage continuous growth until the market is fully matured (e.g. schemes with risk sharing options)
2. Signposting the role of geothermal in UK Net Zero efforts	Improving visibility of geothermal energy technologies in UK government strategies		Defining long-term targets for the sector
3. Improving data availability and accessibility	Supporting the reviewing, processing and sharing of legacy data	Developing a single geothermal data platform for publicly available data sets and geothermal information	Government supported exploration programmes Introducing data sharing obligations
4. Reviewing the legal status, regulation and licensing of geothermal energy		Identifying a regulatory body Defining geothermal energy as a natural resource Streamlining existing regulations	Licensing system for deep geothermal projects
5. Understanding public attitudes towards geothermal energy	Researching public perception to enable a positive public experience with geothermal energy		
6. Facilitating communication between stakeholder groups	Supporting communication between stakeholder groups to establish overarching stakeholder/industry body	Developing specialist groups that advise government	

1 Introduction

1.1 CONTEXT OF EVIDENCE REPORT

This report provides the evidence base that underpins the 'UK Deep Geothermal Energy White Paper', commissioned by the North East Local Enterprise Partnership (North East LEP) and funded by the Department for Energy Security and Net Zero (DESNZ) and North East and Yorkshire Net Zero Hub.

This report includes a review of the wider geothermal landscape, focussing on countries with similar geothermal resources and opportunities, and assimilating relevant learnings (Chapter 2). Assessing the available geothermal resources of the UK (Chapter 3) and highlighting potential regional economic and social impacts of geothermal energy project deployment, it presents how geothermal could contribute to the UK net zero agenda and related policy goals (Chapter 4). Stakeholder engagement has been an important component in developing this white paper. Documentation of the key challenges facing the sector (Chapter 5) along with the actions required for enabling wider deployment of deep geothermal technologies has provided the basis for a wider policy analysis, which has identified next steps for developing the sector (Chapter 6).

A development roadmap for delivering a typical geothermal project has also been provided to better inform non-technical stakeholders, specifically policy makers, regulators and potential clients of the stages involved in developing deep geothermal projects (Appendix 4).

Energy overall is a reserved matter and hence the responsibility of the UK government. However, the devolved nations have some devolved responsibilities for their energy policy, including how to achieve the nationally set decarbonisation targets. Therefore, some variations exist across the UK in terms of the engagement with and support for geothermal energy.

Over the last decade, the Scottish government has supported several studies to explore the potential of geothermal energy in Scotland as a source of low-carbon heat,[4] including a report looking at the potential for deep geothermal energy in Scotland.[5] In 2014, it established a temporary Geothermal Energy Expert Group to provide advice on how to kickstart the geothermal industry in Scotland and funded several feasibility studies that assessed the technical feasibility, economic viability, and environmental sustainability of the deep geothermal resource at several sites across Scotland.[6,7,8]

In Northern Ireland, geothermal energy was identified in the 2021 Energy Strategy for Northern Ireland[9] as an important Net Zero technology. In recognition of this, the Department for the Economy (DfE) committed in its Action Plan 2022[10] to progress geothermal demonstrator projects. DfE set up a Geothermal Advisory Committee (GAC) and commissioned a series of reports that assess the potential, policy landscape and vision for

[4] Scottish Government. Renewable and low carbon energy. Geothermal Energy.
[5] AECOM (2013) Potential for deep geothermal energy in Scotland: study volume 1 and volume 2
[6] Feasibility Report of a Deep Geothermal Single Well, Aberdeen Exhibition and Conference Centre
[7] Guardbridge geothermal technology demonstrator project: feasibility report
[8] Hill of Banchory geothermal energy project: feasibility report
[9] NI Executive (2021) Northern Ireland Energy Strategy 'Path to Net Zero Energy'
[10] NI Executive (2022) Energy Strategy for Northern Ireland. The Path to Net Zero Energy Action Plan 2022.

geothermal energy in Northern Ireland.[11,12,13,14] In 2022, the then Economy Minister Gordon Lyons announced support (of up to £3 million) for geothermal demonstrators, with the work to be commissioned and carried out in 2023. The project comprises two geothermal exploratory and feasibility studies that will be used to better understand the subsurface and to identify sites to drill and install one shallow and one deep geothermal system in Northern Ireland (NI).

Note that Underground Thermal Energy Storage (UTES)[15] is not considered in this report. While it may be applicable in shallower parts of sedimentary basins, the geological, regulatory and policy requirements for UTES can differ. Research on UTES is progressing, including for high-temperature thermal storage applications, and we recommend that ongoing projects, such as the UK-funded ATESHAC project[16] and the EU-funded PUSH-IT project[17] are monitored for outputs relating to geological feasibility, and policy and regulations, respectively.

1.2 DEFINITIONS AND TECHNICAL CONTEXT

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.[18] It 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[19] as well as from residual heat released during the Earth's formation.[20] Heat moves from within the Earth to the surface and gives rise to an increase in temperature with increased depth - the geothermal gradient. The geothermal gradient in the UK averages around 27°C/km, but locally it can exceed 35°C/km.[21] Average UK subsurface temperatures at 1,000 m, 3,000 m and 5,000 m are consequently around 40°C, 90°C and 150°C, respectively. In the shallow subsurface, additional heat is stored from solar radiation and from heat losses from building basements and underground infrastructure, such as tunnels and buried services. Raised subsurface temperatures are noted beneath many urban areas in the UK and worldwide — a phenomenon termed subsurface urban heat island (SUHI) (see references in Abesser & Walker, 2022[22]).

There is no clear delineation between shallow and deep geothermal. The term "**deep geothermal**" is 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 mean systems that produce heat in the 50-200°C range of medium temperature (i.e., steam or water). At the average UK geothermal gradient, this temperature range is typically achieved at depths of 1.4 km to 7 km. It may be regarded as medium-high grade heat, suitable for multiple uses including direct use for space heating, industrial and horticulture use or power generation.

Exploitation of deep geothermal systems requires the drilling of deep wells to reach these higher temperature heat resources. 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

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[11] Raine, R. J. & Reay, D. M. (2021). Geothermal energy potential in Northern Ireland: summary and recommendations for the Geothermal Advisory Committee. Geological Survey of Northern Ireland. 30 pp.
[12] Palmer, M. et al. (2022). Net zero pathways: Building the geothermal energy sector in Northern Ireland. Department for the Economy. Technical Report, pp. 1–136.
[13] Palmer, M. et al. (2022). #NIGeothermalWeek: Defining the vision for geothermal energy in Northern Ireland. Department for the Economy. Technical Report, pp. 1–54.
[14] Arup & BGS (2022). Research into the Geothermal Energy Sector in Northern Ireland. Geothermal Technology and Policy Review. 86 pp.
[15] Gluyas, J.G. et al. (2020). The theoretical potential for large-scale underground thermal energy storage (UTES) within the UK. Energy Reports, 6, 229-237.
[16] https://www.imperial.ac.uk/earth-science/research/research-groups/ateshac/
[17] https://www.push-it-thermalstorage.eu/
[18] European Commission (2009). Directives 2009/28/EC; 2001/77/EC and 2003/30/EC
[19] Davies, J H et al. (2010). Solid Earth, Vol 1, 5–24; Jaupart, C. et al. (2016). Lithos, 262, 398–427.
[20] Anuta, J. (2006). Penn State University; Williams, Q. (1997). Scientific American. October 2016.
[21] Busby, J. (2014). Geothermal energy in sedimentary basins in the UK. Hydrogeology Journal, 22, 129–141
[22] Abesser C. & Walker, A. (2022) Geothermal Energy, POSTbrief 46. 70 pp.

heat or, in some areas of the UK, for power generation. Although the theoretical geothermal energy resource is enormous, the current high costs of drilling restrict the economically viable exploitation of geothermal energy to areas with specific geological settings. As technologies improve and new extraction methods develop, more of the currently inaccessible resource will become available.

Shallow and deep technologies are compatible and combinable across the spectrum of depths and temperatures. Heat pumps can be used in conjunction with geothermal projects, for example to support cascading use of the geothermal water (i.e. consecutive use of the produced steam/water for more than one application, typically with decreasing temperature requirements) or to boost temperatures from moderately deep wells (500-1,000 m) to achieve the required operational temperatures for the heat network. Such hybrid systems benefit from higher temperatures at depth while avoiding the high capital costs and risks associated with even deeper drilling.

Different reporting codes and systems have been developed for the classification of geothermal energy resources. Generally, they distinguish between (1) all thermal energy contained in the rocks, sediments and/or soils beneath the Earth's surface and any fluids contained within; (2) the fully evaluated recoverable thermal energy and (3) a range of additional categories that reflect whether the source has been proven, the socio-economic viability of extraction and the level of confidence in the geothermal energy estimate. Terminology between the different classification schemes can be contradictory.

In this paper, mainly estimates of the **"geothermal potential"** or **"heat in place" is reported,** which is all of the thermal energy contained in the rocks, sediments and/or soils beneath the Earth's surface and any fluids contained within at a given point in time.

Only a small fraction of this energy can be extracted due to physical, technical and socio-economic constraints. Estimating the recoverable fraction requires, amongst other things, direct evidence of the existence of a significant quantity of recoverable geothermal energy. This requires drilling to the geothermal target as well as testing, sampling and/or logging of the wells to confirm the geothermal energy source and reservoir properties. In the UK, there are only a few "Known Geothermal Energy Sources", i.e. geothermal targets where the existence of a significant quantity of geothermal energy has been demonstrated.

In this study, we do not report feasibility of potential exploitation in the areas identified with geothermal potential. Also, we aim to avoid using the terms 'resource' or 'reserve' to describe estimates of the inferred geothermal heat or power potential. Those terms have specific meanings relating to the commerciality, socio-economics and environmental sustainability of the heat energy which vary between the different reporting codes; there are also variations from the classification terminology used in oil and gas.

Under the United Nations Framework Classification for Resources (UNFC-19)[23] (which has been adopted by the International Geothermal Association)[24], for example, the term "resource" is reserved to define the cumulative quantities of geothermal energy that will be extracted from the available geothermal energy source. Hence, the term is only applicable to areas where the existence of a significant recoverable geothermal energy has been proven (i.e. Known Geothermal Sources).

Where the term "geothermal resource" is used in this report, it is intended as a collective term referring to geothermal energy generically (like "natural resource") without connotations of commerciality.

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[23] UNECE (2019) Supplementary Specifications for the application of the United Nations Framework Classification for Resources (Update 2019) to Geothermal Energy Resource

[24] https://unece.org/sustainable-energy/sustainable-resource-management/unfc-and-geothermal-energy

1.3 CONVENTIONAL GEOTHERMAL SYSTEMS AND TECHNOLOGIES

There are many fit-for-purpose classifications for deep geothermal systems in use worldwide.[25] In the UK context, to date, a combination of classifications is used. One widely used classification is based on geological reservoir characteristics and exploitation strategy. It distinguishes between hydrothermal and petrothermal systems (Figure 1).[26] Hydrothermal systems rely on the availability of a porous and permeable reservoir, where water flows either in the rock matrix, fracture or faults, from which hot water can be produced. Petrothermal systems are characterised by rocks in which natural flow of water is limited (tight rocks) and which need to be artificially stimulated (hydraulically or thermally fractured and/or acidised) to be able to produce or circulate water.[27] In the UK to date, because of its geological setting, the terms “hydrothermal” and “petrothermal” are loosely used to refer to systems used for production of heat and those used for production of power (Figure 1), respectively. Production of geothermal direct-use heat (i.e., heat can be used directly for heating without thermal boost from an electrical heat pump) requires temperatures in excess of 50°C, while generation of electricity at scale needs higher enthalpy, the right combination of sufficient flow and pressure together with higher temperatures, typically above 150°C, although Organic Rankine Cycle (ORC) power generation is achievable at temperatures greater than 80°C.

Another classification that is widely used in the UK is based on rock type. In this classification, the term ‘Hot Sedimentary Aquifer’ (HSA) describes a porous and permeable sedimentary rock containing water (in the matrix, fractures or faults) at elevated temperatures. In contrast, the term ‘Hot Dry Rock’ (HDR) is used to describe a tight (i.e., not very permeable) rock generally of igneous plutonic or metamorphic origin (such a granite or a gneiss). The terms hydrothermal and HSA, and petrothermal and HDR are often used synonymously. A more detailed description of the UK geothermal systems is provided in Section 3.4.

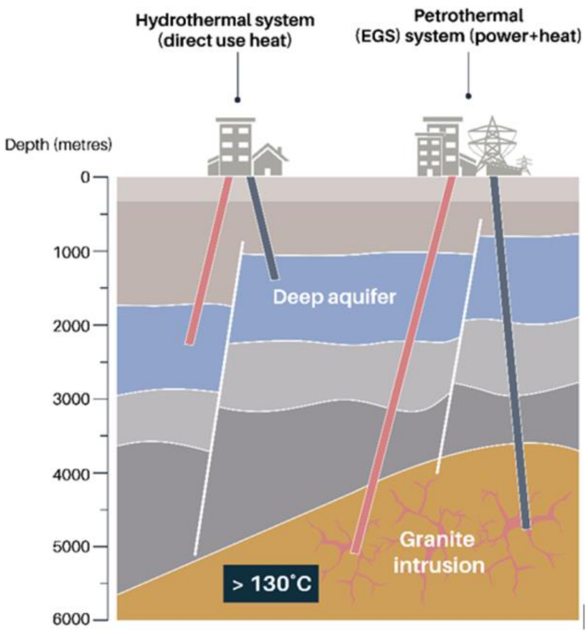

Figure 1: The main types of deep geothermal systems (not to scale) for heat and power generation in the UK (BGS © UKRI 2023).

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[25] Breede, K. et al. (2015). Overcoming challenges in the classification of deep geothermal potential. Geothermal Energy Science, vol. 3, pp. 19–39.
[26] Moeck, I. S. (2014). Catalog of geothermal play types based on geologic controls. Renewable and Sustainable Energy Reviews, vol. 37, pp. 867–882.
[27] Mijnlieff, H. F. (2020). Introduction to the geothermal play and reservoir geology of the Netherlands. Netherlands Journal of Geosciences, vol. 99, e2.

Several technologies are available to access deep geothermal energy. The main technologies are described below. There are also several novel geothermal concepts and innovative drilling technologies that are being developed. These are described in Section 4.7.

1.3.1 Geothermal doublets for geothermal direct-use heating

Traditionally, geothermal exploitation has relied on the presence of water-bearing and permeable rocks at depth through which hot fluids circulate. These so-called hydrothermal systems (Figure 1) or geothermal aquifers can be found in deep sedimentary basins across the UK. They can be exploited by drilling two (or more) deep wells: one for producing the hot water or steam (producer) from the permeable, water-filled rocks and one for re-injecting the cooled water (injector) after heat extraction back into the geothermal aquifer. This so-called geothermal doublet design is similar to that of open-loop ground source heat pump systems. For deep **geothermal direct-use**, the extracted heat is typically high enough (> 50°C) for direct use heating (via a heat exchanger) without requiring a thermal boost from an electrical heat pump (Figure 2a).

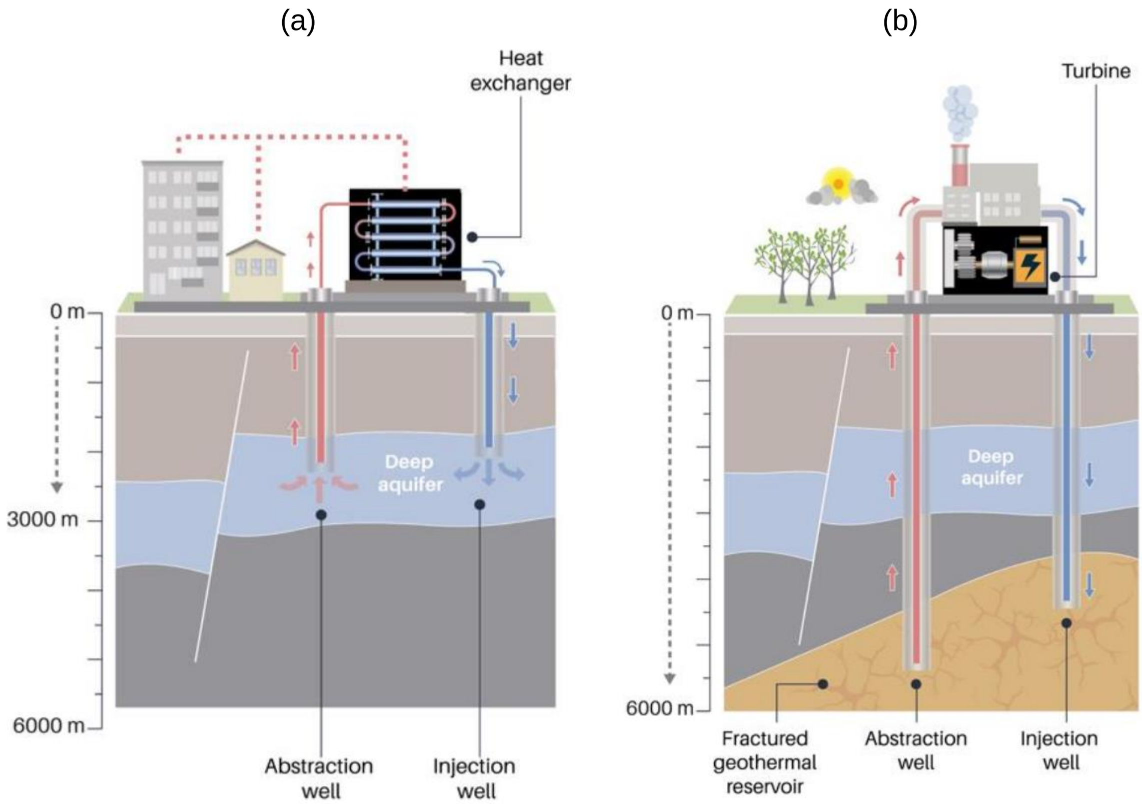

Figure 2: Geothermal doublets (not to scale): (a) used to pump and reinject water from a deep hydrothermal system and (b) drilled into a deep fracture system to create an enhanced geothermal system (EGS) (BGS © UKRI 2023).

1.3.2 Enhanced Geothermal Systems (EGS)

Where there is hot rock but insufficient natural fluid and/or permeability within the system to transport this heat to the surface (petrothermal system), Enhanced Geothermal Systems (EGS) (Figure 1) are created. In the UK, the term is used to describe naturally fractured geothermal systems in rocks that are not traditional geothermal aquifers, such as granites, and where some hydraulic and/or thermal fracturing (injection of water under high pressure) or acid dissolution may be needed to enhance existing, or create new, fluid pathways. The basic design consists of a well doublet drilled into a fracture system. A closed circulation system is created by extraction of water from the production well (producer) and re-injection into the second well (injector). EGS are typically developed for **power generation**, which typically requires temperatures of more than 150°C, although it can also provide heating to nearby buildings to make the system more profitable (Figure 2b).

1.3.3 Deep Geothermal Single Well

Deep Geothermal Single Wells (DGSW), also called coaxial (open-loop or closed-loop) boreholes or single borehole heat exchangers (Figure 3), are an adaptation of established shallow geothermal technologies (standing column well) that have been modified for use in single deep wells.[28] Application in deep wells is still in its infancy and only a few systems have been implemented worldwide and with mixed success.[29]

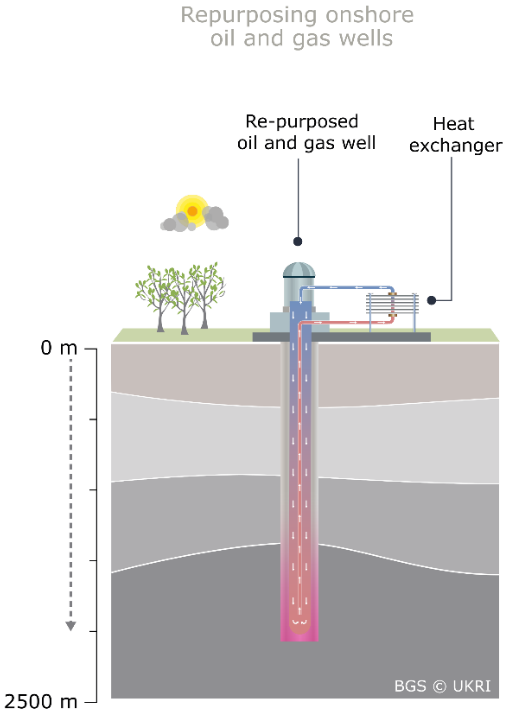

Figure 3: Single, coaxial borehole heat exchanger for geothermal heat production (BGS © UKRI 2023).

DGSWs typically consist of two concentric tubes: one carrying fluid down and the other carrying fluid back up through the centre, exchanging heat during fluid counterflow. 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. The technology is less reliant on the availability of a deep aquifer and has potential for application in most areas of the UK[30] (like shallow geothermal closed-loop systems). The power output from single wells 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

[28] Brown, C. S., & Howell, L. (2023). Unlocking deep geothermal energy in the UK using borehole heat exchangers. Geology Today, 39(2), 67-71.
[29] Falcone, G. et al. (2018). Assessment of Deep Geothermal Energy Exploitation Methods: the Need for Novel Single-Well Solutions. Energy, vol.160, pp. 54–63.
[30] Collins, M. et al. (2017). The Development and Deployment of Deep Geothermal Single Well (DGSW) Technology in the United Kingdom. European Geologist Journal, vol. 43, pp. 63–68.

returns.[31] Other technologies for heat exchange in single wells include conventional U-pipes as used in shallow closed-loop systems), but lower fluid volumes in these system means that they deliver lower heat loads for the same depth of borehole. At this stage of technology development, deep geothermal single wells are most suited for heat applications, but power generation may become feasible in the future.

1.4 STAKEHOLDER ENGAGEMENT: DATA AND METHODOLOGY

Stakeholder engagement formed an important part of this study. It was carried out to:

A. Identify key opportunities and challenges facing the sector, i.e. technical (including availability of data), commercial, regulatory, market, environmental, subsidy and policy barriers;
B. Identify actions and interventions needed to accelerate geothermal energy delivery at scale in the UK;
C. Map out the potential UK project pipeline;
D. Gather views and data relating to socio-economic benefits, maturity of supply chain and its capabilities for delivery;
E. Identify opportunities for other sectors to support/service the deep geothermal energy sector with skills, technologies, supplies.

Stakeholder engagement undertaken in this study included:

- Review of existing stakeholder evidence
- Virtual stakeholder workshop
- Online stakeholder survey
- Individual stakeholder interviews
- Steering group workshop.

1.4.1 Review of existing stakeholder evidence

In the past two/three years, several consultations and workshops have been conducted to understand stakeholders' views on opportunities and challenges for geothermal energy in the UK. Mostly, these have focussed on the development of deep geothermal projects,[32,33,34] engaging with a range of participants from industry, regulators and academia.

In 2022, the Environmental Audit Committee (EAC) carried out an inquiry into geothermal technologies,[35] which attracted 31 submissions of written evidence. The inquiry focussed on Deep Geothermal Systems and Mine Water Energy Systems, investigating the potential scale of their deployment in the UK to provide heat and power. The submitted evidence was analysed by Arnhardt et al. (2023) in a separate study.[36]

Prior to engaging with stakeholders for this white paper, we considered evidence from the available studies (listed above) and from the submissions to the EAC inquiry to extract key themes for further consultation in the workshop and online survey.

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[31] Westaway, R. (2018). Deep Geothermal Single Well heat production: critical appraisal under UK conditions. Quarterly Journal of Engineering Geology and Hydrogeology, vol. 51, pp. 424–449.
[32] Abesser, C. et al. (2020). Unlocking the potential of geothermal energy in the UK. British Geological Survey Open Report, OR/20/049.
[33] Abesser, C. et al. (2023). Visualising geothermal regulations for the UK. Research brief. Unconventional Hydrocarbons in the UK Energy System (UKUH) project. Newcastle University.
[34] Hambley et al. (2023) Regulation and public decision making in geothermal energy – Workshop report, NERC Unconventional Hydrocarbons in the UK Energy System (UKUH) project.
[35] Technological Innovations and Climate Change: Geothermal Technologies
[36] Arnhardt, C. et al. (2023). Geothermal Technologies - Analysis of written evidence from the Environmental Audit Committee inquiry, BGS Internal Report, IR/23/001.

1.4.2 Virtual Workshop, online survey and individual interviews

The virtual workshop investigated objectives (A) and (B). It was attended by 34 stakeholders from 24 organisations, including geothermal developers, clients, service providers (consultants, drillers), regulators and investors (Table 1 in Appendix 2).

The workshop explored the themes identified by the initial review evidence and identified key actions and interventions for accelerating geothermal energy development in the UK.

Outputs from the workshop were used to develop questions for the online survey. The aim of the survey was to consult on and prioritise the actions identified by workshop participants as well as to gather information relating to objectives (C) and (D). The survey was sent to 154 recipients from industry, finance, regulators and academia. It consisted of 25 questions and received 59 responses (Table 1 in Appendix 2).

Seven stakeholder interviews (and several informal enquiries) were undertaken with stakeholders involved in geothermal project development, drilling, finance and regulation. The aim of the interviews was to gather project specific data and to fill any gaps relating to objectives (A-D).

Outputs from stakeholder evidence and views are described in Chapters 4.1 and 5 and formed the basis of the policy analysis in Section 6.2. A summary of the outputs is given in Appendix 2 in the form of graphs, including details on the representation of different stakeholder groups at the different engagements.

In the following report, the terms “EAC evidence”, “Stakeholder workshop”, “Stakeholder survey” and “Stakeholder interviews” refer to the analyses and engagement undertaken in this study as described above.

2 Geothermal landscape review

This section summarises a review of the geothermal energy landscape in Europe. It considers five countries, focussing particularly on France, Germany, Belgium and The Netherlands, because of their similar geothermal prospects to the UK in terms of type of geothermal systems and achievable temperature range (see country descriptions in Arup & BGS (2023)[14]). Switzerland is also included in some sections to provide additional insights related to policy measures. However, its geothermal potential is considerably different from the UK.

Consideration was given to market context and costs as well as to regulation and available policy mechanisms for geothermal technologies to ensure that maximum insights and learning can be extracted from this review. The review draws on information available in country-specific geothermal reports, policy documents, academic literature, and stakeholder accounts from our previous research, and in some instances on data derived directly from stakeholders in the respective countries.

Some recent numbers for the UK market and costs are included here for comparison or reference. However, a comprehensive review of the current UK geothermal landscape can be found in Abesser & Walker (2022)[37] and thus is not repeated here.

2.1 EUROPEAN MARKET CONTEXT

In Europe, the market leaders for deep geothermal heating are Iceland and Turkey. Located in tectonically and volcanically active regions near plate boundaries, both countries have geologically favourable settings for high-temperature geothermal energy exploitations. Amongst the European countries that are located away from volcanically active regions (i.e. in stable continental setting), France, Germany and the Netherlands are market leaders for geothermal heating.

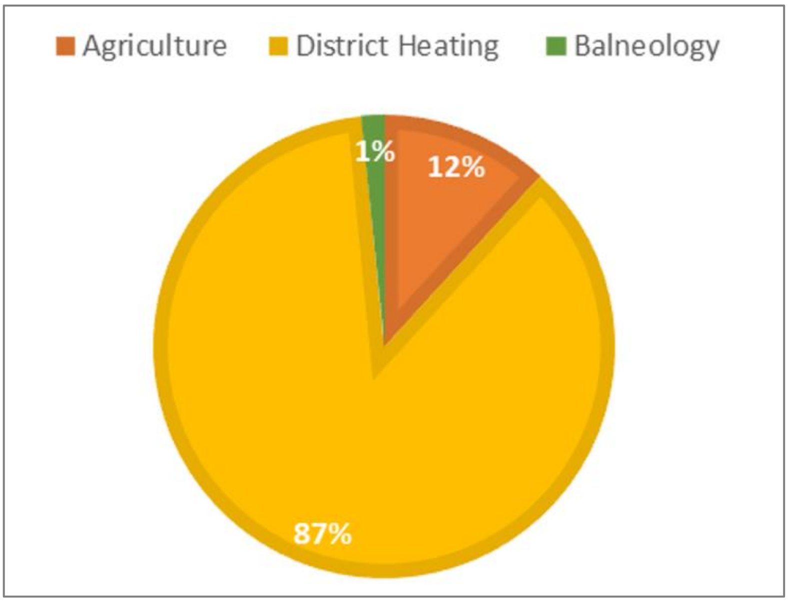

Figure 4: Use of geothermal heat production for different sectors in France. Based on figures for 2020 from Sanner (2022).[39]

[37] Abesser, C. & Walker, A. (2022). Geothermal Energy, POSTbrief 46.

There were 72 deep geothermal heating projects in operation in **France** in 2020 with an overall capacity of more than 570 MW_{th}[38] (MW_{th} and MW_e denote installed capacity for heat and power generation, respectively). The annual heat production is 2,000 GWh_{th}[39] mainly for district heating but also for greenhouses, fish farming, and swimming pools and baths (Figure 4). France currently operates one geothermal power plant in Soultz-sous-Forêts and another one in its overseas territories (Guadeloupe, French West Indies). **Germany** has 190 deep geothermal heating projects and more than 10 geothermal power or combined heat and power projects, with several new plants being commissioned.[40] In the last 10 years, the total installed capacity for geothermal heat and power generation (given as MW) in Germany doubled from 200 MW in 2012 to 400 MW in 2022. This is expected to approach 850 MW by 2030 with an investment of USD 1.5 billion.[41] Since 2000, the geothermal industry in Germany has generated €16.7 billion[42] and created 35,900 jobs.[43] The **Netherlands** had 31 operational deep doublets at the start of 2022 (saving 342,000 tonnes of CO_2 compared to using gas) and a further 19 projects in development. It currently has an installed capacity of approximately 300 MW_{th}[44] but is expected to add 1 GW capacity from 2022 to 2030. There are currently no geothermal power projects in the Netherlands due to a strategic decision by the Dutch government to focus on geothermal heating.[45] The geothermal sector in **Belgium** is immature compared to that of other countries in this review. It has four operational deep geothermal projects for district heating with a total installed capacity of 25 MW_{th}.[46]

For comparison, the total installed capacity for deep geothermal systems in the UK is ~8.1 MW_{th} for geothermal heating (including some 'shallow' mine energy schemes).[47] Two deep geothermal power projects are in development, but, as yet there is no generation of geothermal power in the UK, but one of the projects has now stared to provide heat to the Eden Project biomes and offices.

2.2 PROJECT COSTS

A list of the overall project expenditure for a 14 MW_{th} geothermal doublet (two wells drilled to 3 km depth) is shown in Table 1. It was developed as part of a White Paper on the Fundamental Cost Price Reduction Program Geothermal Heat 2021[48] written by Energie Beheer Nederland (EBN) to provide a hypothetical reference case for planners and decision makers. EBN are the Dutch equivalent to the UK's North Sea Transition Authority. In addition to hydrocarbons, EBN oversee the exploration, management and licensing of geothermal energy and are a non-operating partner in most of the projects. The reference case is based on data from completed projects and projects in development that were shared with EBN in confidence. The data were used to determine typical well depths and cost for geothermal heat projects in the Netherlands and aggregated into the different categories. A range of

[38] Schmidlé-Bloch, V. et al. (2022). Country Update for France, European Geothermal Congress 2022, Berlin, Germany.
[39] Sanner (2022) Summary of EGC 2022 Country Update Reports on Geothermal Energy in Europe. European Geothermal Congress 2022, Berlin, Germany
[40] Weber, J. et al., (2022). Country Update for Germany. European Geothermal Congress 2022, Berlin, Germany.
[41] Rystad Energy (2022). Full steam ahead: Europe to spend $7.4 billion on geothermal heating, capacity to reach 6.2 GWt by 2030.
[42] Bundesministerium für Wirtschaft und Energie (BMWi) (2021). Zeitreihen Erneuerbare Energien. Time series for the development of renewable energy sources in Germany, Status September 2022.
[43] Bundesministerium für Wirtschaft und Energie (BMWi) (2023). Bruttobeschäftigung durch erneuerbare Energien 2000 bis 2021.
[44] Provoost, M. & Agterberg, F. (2022). Country Update for The Netherlands. European Geothermal Congress 2022, Berlin, Germany.
[45] Dutch Association Geothermal Operators, Stichting Platform Geothermie, Stichting Warmtenetwerk and EBN (2018). Master Plan Geothermal Energy in the Netherlands.
[46] Dupont, N. et al. (2022). Country Update for Belgium. European Geothermal Congress 2022, Berlin, Germany.
[47] Abesser & Jans-Singh (2022) 2021 United Kingdom Country Report, IEA Geothermal Technical Collaboration Programme
[48] EBN (2021). Whitepaper Integraal Kostprijsreductie Programma Aardwarmte Kostprijsreductie Aardwarmte, December 2021.

stakeholders provided feedback on the case, including geothermal energy companies, industry associations, service companies and heat companies. The costs are correct for the year 2021.

Table 1: Typical expenditure in Euros for a geothermal doublet with capacity of 14 MW_{th} consisting of 2 diverted wells drilled to 3 km depths (geology not specified – likely to be Permo-Triassic sandstone) (source: EBN[48])

Construction Phase	**Development expenditure (DEVEX)**	Preliminary study	150,000
		Reconnaissance	590,000
		Development	1,250,000
		Financing costs and due diligence	510,000
		Realisation preparations	440,000
		Contingency	120,000
	Total DEVEX	incl. contingency	3,060,000
	Capital expenditure (CAPEX)	Generic	2,780,000
		Well site and conductors	1,690,000
		Drilling rig (incl. mob, demob)	3,450,000
		Services and consumables	6,720,000
		Materials	6,990,000
		Above-ground installation	6,900,000
		Contingency	2,853,000
	Total CAPEX		31,383,000
Operation Phase	**Operational expenditure (OPEX)**	Annually	620,000
		Reinvestments (costs per year)	230,000
		Annual electricity costs	700,000
		Contingency (per year)	40,000
	Annual OPEX	incl. contingency	**1,590,000**
	Total OPEX (30 years)	incl. contingency	**47,700,000**
End of life	**Decommissioning**	Wells and installations	1,500,000
	Total Decommissioning		**1,500,000**
Total fixed costs (DEVEX, CAPEX, Decommissioning)			**35,943,000**
Total variable costs (OPEX) over 30-year lifespan			**47,700,000**

Development expenditure (DEVEX), including exploration, design and planning make up approximately 9% of the total fixed costs (i.e. excluding OPEX) and 4% of the overall project costs (Table 1, Figure 5) for a project with a 30-year lifespan. These costs can vary considerably depending on the availability of existing data. Typically, exploration includes some seismic data acquisition. Figures provided by UK service providers give costs of ~£6,000 per line kilometre for a generic two-dimensional (2D) seismic survey and ~£75,000 per kilometre for a generic three-dimensional (3D) seismic survey. Additional costs arise for planning, permitting, stand-by and compensation costs, data processing as well as for mobilisation, testing and demobilisation. The latter is estimated to lie in the order of

~£50,000 for a generic project but can be much higher in urban environments where a denser receiver grid layout is required to compensate for background noise and restricted source power. A detailed appraisal of the costs involved in a seismic survey in a semi-urban environment is included in Box 1. The cost of seismic acquisition reduces if there is a portfolio of projects for which seismic acquisition is required.

Box 1: Cost of seismic data acquisition for 2D and 3D seismic surveys in urban / semi urban settings (Source: Rees Onshore Seismic Ltd.).

Cost of seismic data acquisition in urban / semi urban settings

Survey type: 2D

Survey Size: 50 km

Source Type: Vibroseis 2 x large vibrator active per point

Receiver Spacing: 20 m (Total points 2,500)

Source Spacing: 40 m (Total points 1250)

Location: Unknown – assumed semi urban/town/road. Off road 20%

Budget Costing based on February 2023 rates:

1. Mob/Demob: £140,000
2. Permit and Project Setup: £55,000
3. Vib Crew: £240,000
4. Reimbursables: £40,000
5. Data Processing: £24,000

Total for project £499,000

Survey type: 3D

Survey Size: 10.9 km^2

Source Type: Vibroseis 2 x large vibrator active per point

Receiver Spacing: 20 m, lines at 180 m interval (Total points 3,200)

Source Spacing: 20 m, lines at 360 m interval nominal or random depending on area (Total points 1660)

Location: Unknown – assumed semi urban/town

Budget Costing based on February 2023 rates:

1. Mobilisation/testing/demobilisation: £160,000
2. Permit and Project Setup: £60,000
3. Vib Crew: £410,000
4. Reimbursables: £72,000
5. Data Processing: £30,000

Total for project: £732,000

Assumptions:

- Urban environment, all road and track for source, receivers along roads and in private residences.
- Source maybe random depending on road layout.
- Quite dense grid allowing for background noise and restricted source power.
- Project duration – Acquisition Only 4 weeks.
- Project Setup -3-6 months depending on location.
- Time to prepare and acquire will depend on location and time of year, if there is a follow on. project, then additional savings can be achieved.

Capital expenditure (CAPEX) makes up 87% of the total fixed costs (i.e. excluding OPEX) and 37% of the overall project costs (Table 1, Figure 5) for a project with a 30-year lifespan. The cost of drilling, including well completion and testing, remains the primary driver of geothermal project costs. Drilling costs depend on a variety of factors including geology, depth and orientation of the well but also on market conditions and maturity as well as the experience of drilling deep wells in the area. The uncertainty of drilling success further exacerbates the risk that goes into geothermal drilling.

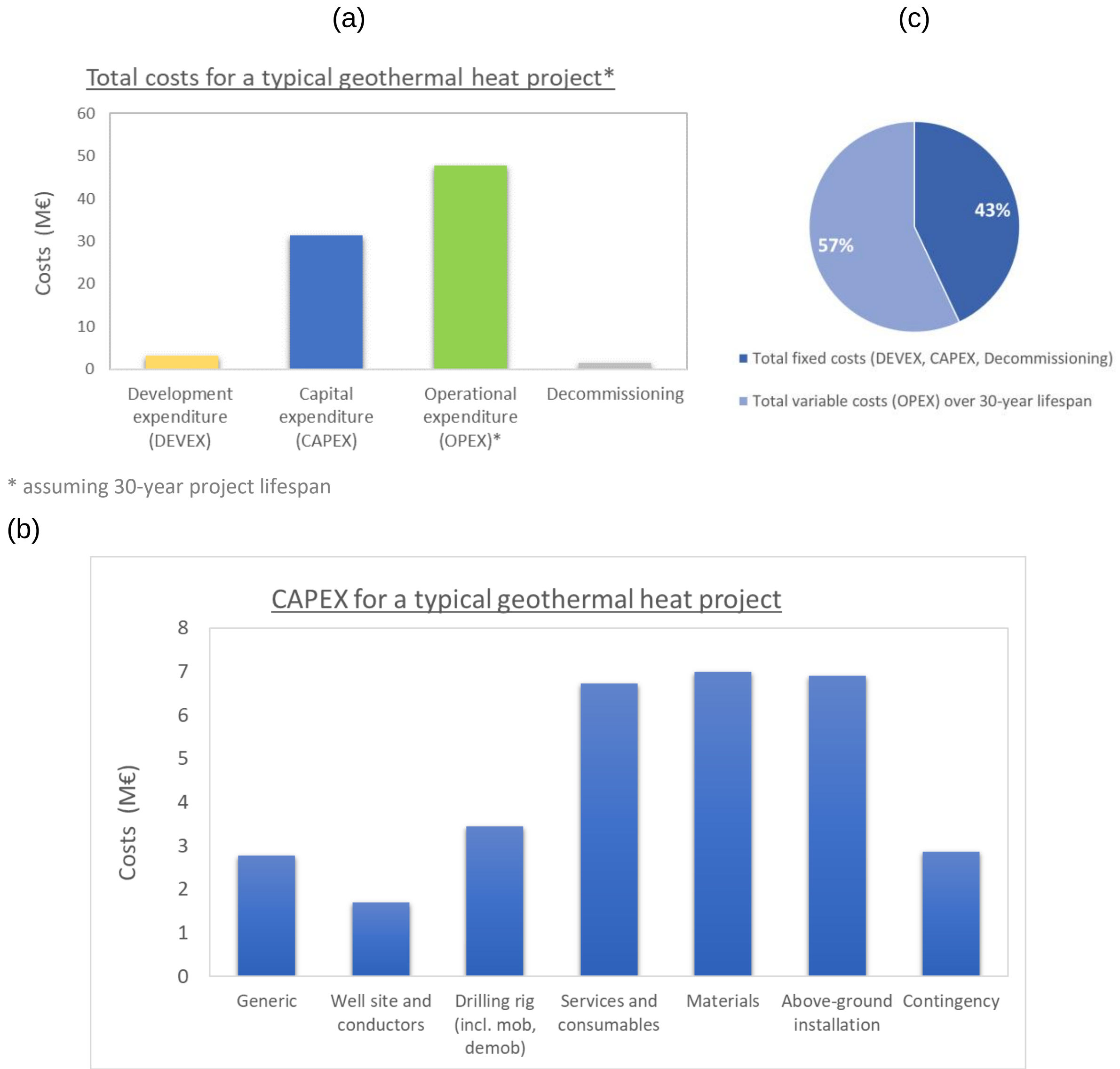

Figure 5: (a) Overall project costs, (b) breakdown of CAPEX for a geothermal heat project and (c) split between fixed and variable costs assuming a *30-year project lifespan (source: EBN)[48] (© North East LEP).

There is limited availability of data on drilling costs for geothermal wells in the UK. Arup (2021)[49] estimated costs in the order of £1.6 to £1.8 million per km depth for 1–2 km vertical wells, i.e. approximating €3.6 to €4 million for a 2-km well. Drilling cost in the Paris basin in 2021 are quoted as €4 to €5 million per well, both for exploration and production wells, giving a total cost of €9 to €10 million for a geothermal doublet.[50]These numbers have been

[49] Arup (2021). Deep Geothermal Energy – Economic Decarbonisation Opportunities for the United Kingdom.
[50] Antics, M. (2021). Planning geothermal district heating projects. Lessons learned from France

confirmed by stakeholders. Assuming an average drilling length for European geothermal district heating projects of around 2 km,[41] these numbers translate to drilling costs of £1.8 to 2.2 million per km. For the Netherlands, stakeholders reported that the cost of an exploration well was in the range of €7 to €10 million. Assuming average drilling depths of 3 km for typical heat projects in the Netherlands,[48] these numbers translate to drilling costs of £2 to 3 million per km.

This difference is likely to be due to a rise in commodity prices over the past decade which has impacted costs of drilling and well completion, also reflecting the lower maturity of the Dutch market. Stakeholders elsewhere have also reported an increase in drilling costs as well as higher demand for parts, equipment and skills from a growing market in the last few years.

Drilling costs are seen to reduce over time for a given area and/or geology, with pilot wells tending to be the most expensive. As more wells are drilled the experiences gained allow drilling to be completed faster, resulting in cost reductions. In the SW Molasse Basin of Germany, for example, drilling time reduced from 20–24 days per km for the first group of wells drilled in 2008 to less than 12 days per km for the last well drilled in 2016. The reduction in drilling time directly translated into a reduction in average drilling cost (excluding site preparation and well testing) from €1.4 to €1.1 million per drilled km.[51] In a US study, cost reduction of up to 25% was estimated to occur during drilling of the first 10 wells, after which costs level off.[52]

Operational expenditure (OPEX) are variable costs that include repairs and maintenance costs as well as electricity costs for operating the pumps. The annual OPEX is equivalent to about 4% of the overall fixed costs. Over the operational lifespan of the project, OPEX makes up 57% of the overall project costs for a project that operates for 30-years. These costs vary depending on a range of factors, including the depth of the geothermal target. Careful consideration must hence be given to the significant pumping power that may be needed to lift and reinject the geothermal water (brine) from the hydrothermal reservoir.

Decommissioning makes up only 4% of the total fixed costs (i.e. excluding OPEX) and 2% of the overall project costs (Table 1, Figure 5) for a project with a 30-year lifespan.

2.3 LEVELISED COST OF HEATING (LCOH) AND ELECTRICITY (LCOE)

2.3.1 Heating

The average weighted levelised cost of heating (LCOH) for European (excluding Iceland) geothermal projects averaged around 37 €/MWh,[41] but there is some variation between and within countries. The region of Ile-de-France (France) and the Molasse Basin (Germany) have some of the lowest LCOH of 15–55 €/MWh[53] and 30–40 €/MWh, [54] respectively. Projects in other areas of Europe like the Rhine Graben (Germany), the Netherlands and Switzerland have LCOH of 50–75 €/MWh[54], 65 €/MWh[54] and 64 €/MWh,[41] respectively. The variations are due to factors like project size, well depth and the ground-level temperature.[37] Deeper drilling tends to increase the LCOH but as projects get larger the contribution of drilling costs to total project costs tends to decrease. A colder location puts more stress on the system and will result in a less favourable LCOH over its lifetime.[41] The higher project costs seen in the more recently developed areas also reflect a general rise in drilling cost over the past few years as well as a general rise in commodity prices.

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[51] Schulz, I. et al. (2017). Factors for the success of deep geothermal projects – experience from the Bavarian Molasse Basin. Erdöl, Erdgas, Kohle, vol. 133 [in German]
[52] Lukawski, M.Z. et al. (2014). Journal of Petroleum Science and Engineering, vol. 118, pp. 1–14.
[53] ADEME (2020). Coûts énergies renouvelables et de récupération
[54] Stakeholder, pers. comm.

2.3.2 Power

As for heating, geothermal power plant installation costs are site sensitive and show large variation between countries. They are also influenced by the type of installed plant, which in turn, is dependent on the available geothermal resource. Another main driver is the drilling cost. Globally, the average LCOE are given as 38–62 €/MWh.[55] In Europe, data availability is limited and somewhat inconsistent. For France, a value of 160 €/MWh is reported for a 3 MW_e Enhanced Geothermal system with two boreholes and a total installation cost of around €30 Million.[53] For Germany, LCOE is likely to be similar. Reliable figures were not available at the time of writing, but an industry expert surmised that the available Feed-in Tariff for geothermal power of 250 €/MWh makes power projects in Germany sufficiently profitable.[54]

2.4 GEOTHERMAL DISTRICT HEATING NETWORKS

Geothermal energy is widely used in district heating across Europe with networks ranging in capacity from < 1 to 50 MW_{th}. In 2014, there were approximately 250 geothermal district heating systems in operation across Europe with an installed capacity of about 4,400 MW_{th} and an annual estimated production of approximately 13,000 GWh per year. These included district heating networks in Paris (France) where water between 57°C and 85°C is pumped from depths of between 1.5 and 1.8 km with 46 operations providing geothermal energy for about 0.7 million people.[56] Munich (Germany) operates a geothermal district heating network, which is supplied by five geothermal plants producing temperatures of 90°C to 140°C from the limestone aquifer at depths between 2.4 and 5.5 km.[57] The network currently delivers geothermal heating to around 50,000 homes, saving > 75,400 tonnes of CO_2 per year (compared with gas).[58]

Cost of geothermal district heating [EUR/MWh]

[125°C, 120 L/s]

Full load hours \ Interconnection line length [m]	0	2500	5000	7500	10000	12500	15000
2400	50	59	68	77	86.1	95.1	104
2500	49	58	64	75	83.2	91.8	100.3
2600	48	56	64	72	80.5	88.7	97
2700	46	54	62	70	78	85.9	93.9
2800	45	53	60	68	75.7	83.3	91
2900	44	51	59	66	73.5	80.9	88.3
3000	43	50	57	64	71.5	78.6	85.8
3100	42	49	56	63	69.6	76.5	83.4
3200	41	48	54	61	67.8	74.5	81.2
3300	40	47	53	60	66.2	72.6	79.1
3400	39	46	52	58	64.6	70.9	77.2
3500	39	45	51	57	63.1	69.2	75.4
3600	38	44	50	56	61.7	67.7	73.6
3700	37	43	49	55	60.4	66.2	72
3800	37	42	48	54	59.1	64.8	70.4
3900	36	41	47	52	58	63.5	68.9
4000	35	41	46	51	56.8	62.2	67.5
4100	35	40	45	51	55.8	61	66.2
4200	34	39	45	50	54.7	59.8	64.9
4300	34	39	44	49	53.8	58.7	63.7

Figure 6: Costs of geothermal district heating in EUR/MWh depending on full load hours and interconnection line length [m] for production temperatures and rates of 125°C and 120 L/s (litres per seconds), respectively. Redrawn after the Masterplan Geothermie Bayern.[59]

Although there is a high capital expenditure, the fixed operations and maintenance costs are in line with other renewable energies, and variable costs are low. The Masterplan Geothermie Bayern estimates the cost of geothermal heat networks to range between €34

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[55] IRENA (2022). Renewable Power Generation Costs in 2021.
[56] Boissavy, C. et al. (2019). Country Update for France. European Geothermal Congress
[57] Abesser (2021) Geothermal Energy in the UK. Weatherford Geothermal Industry Session, February, 2021
[58] Abesser & Walker (2022) Geothermal Energy. POSTbrief 46.
[59] Masterplan Geothermie Bayern (in German)

and 104/MWh (Figure 6) depending on the load hours and length of the network. In 2013, EGEC derived similar values, estimating thermal district heat to be, on average, €60/MWh.[60]

2.5 DATA AVAILABILITY

Many countries in this review have web-based geographical information system and data portals that provide information and maps of geothermal potential to help developers and policy makers identify opportunities for deployment of geothermal technologies. Availability of such tools has been linked to an increase in interest in geothermal energy.[61] TNO, the Netherlands Organisation for Applied Scientific Research, which includes the Geological Survey (GSN), hosts a very extensive, publicly available suite of databases on the subsurface[62] as well as a geothermal tool (ThermoGIS).[63] The data come from various sources, including from exploration and production companies which must share data with the Ministry of Economic Affairs and Climate under the terms of the Mining Act.[62] Company data are made publicly available five years after acquisition.[64] Public availability of such data as well as their quantity and quality allow exploration companies and the government to predict likely heat output of a planned geothermal doublet with 90% (P90) certainty. This degree of certainty enables the government to provide a risk insurance scheme and it helps companies to get up to 70% bank financing[65] but project financing can still be difficult.

Some countries, such as Germany, Denmark, the Netherlands and Switzerland, have data sharing obligations whereby it is defined by law or as part of a subsidy or licensing conditions that any geological data that is collected as part of geothermal investigations or drilling need to be deposited with a specified public authority, typically the national geological survey. Data availability and access is regarded as an important prerequisite for accelerating the development of a geothermal industry. Where sharing obligations exists, data is either released for public use or used by the country's geological survey for updating publicly available data portals and information systems.

In the Netherlands, a national seismic data acquisition campaign for geothermal, SCAN (Seismische Campagne Aardwarmte Nederland), was conducted from the beginning of 2019 for 3 years. Funded by the Dutch government, SCAN aimed to accelerate the development of geothermal energy projects by enhancing subsurface knowledge, especially in areas with a low data density. It had a budget of about €140 M to explore an area equating to half the Netherlands (equivalent in size to one tenth of the UK) with 2D seismic coverage.[66]

2.6 GOVERNMENT STRATEGY AND SUPPORT

Several countries and regional governments have included geothermal energy in their energy planning and net zero strategies and have commissioned studies to identify the geothermal potential of the country for heat and/or power production or geothermal district heating (e.g., the state of Bavaria, Germany[67] and the Republic of Ireland[68]). Countries like France, Germany and the Netherlands have defined specific targets and strategies for growing their geothermal sector.[69,70] The Dutch government, for example, defined a clear commitment, in the form of a Geothermal Masterplan,[71] to developing geothermal energy in the Netherlands to support its move away from gas (Box 2).

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[60] EGEC (2013). Financing Geothermal Energy July 2013. EGEC Policy Paper
[61] Abesser, C. & Walker, A. (2022). Geothermal Energy, POSTbrief 46.
[62] NLOG. Data Supply.
[63] NLOG. ThermoGIS.
[64] IRENA (2019). Accelerating geothermal heat adoption in the agri-food sector
[65] Richter, A. (2016) The rapid development of geothermal energy in the Netherlands.
[66] SCAN https://scanaardwarmte.nl/
[67] Masterplan Geothermie Bayern (in German)
[68] Blake, S. et al. (2020). An assessment of geothermal energy for district heating in Ireland.
[69] Cariaga (2023). France publishes action plan to accelerate geothermal development. ThinkGeoenergy.
[70] Cariaga (2022) Germany aims for 100 new geothermal projects by 2030. ThinkGeoenergy.
[71] Platform Geothermie (2018). Master Plan Geothermal Energy in the Netherlands.

Box 2: Geothermal policy in the Netherlands

Geothermal policy in the Netherlands

In the last 10 years, the Netherlands has seen an increase in deep geothermal systems from 7 to 31 operational plants. The success has been attributed to the government support for geothermal energy in the form of long-term government visions and financial support. [72]

There is a clear commitment from the government to develop geothermal energy in the Netherlands, and several external drivers precipitated the decision to move away from gas partly triggered by the loss of public acceptance for gas developments.[73] The country's geothermal commitment was first defined in 2011 in the form of a vision for geothermal which in 2018 was translated into a masterplan for geothermal energy, [74] with clear targets and policy support measures. This national geothermal energy strategy was developed by industry foundations (Platform Geothermie, Warmtenetwerk), the Dutch Association of Geothermal Operators (DAGO) and the geothermal energy regulator (Energy Beheer Netherland – EBN) in collaboration with the Ministry of Economic Affairs and Climate and the Ministry of the Interior and Kingdom Relations.

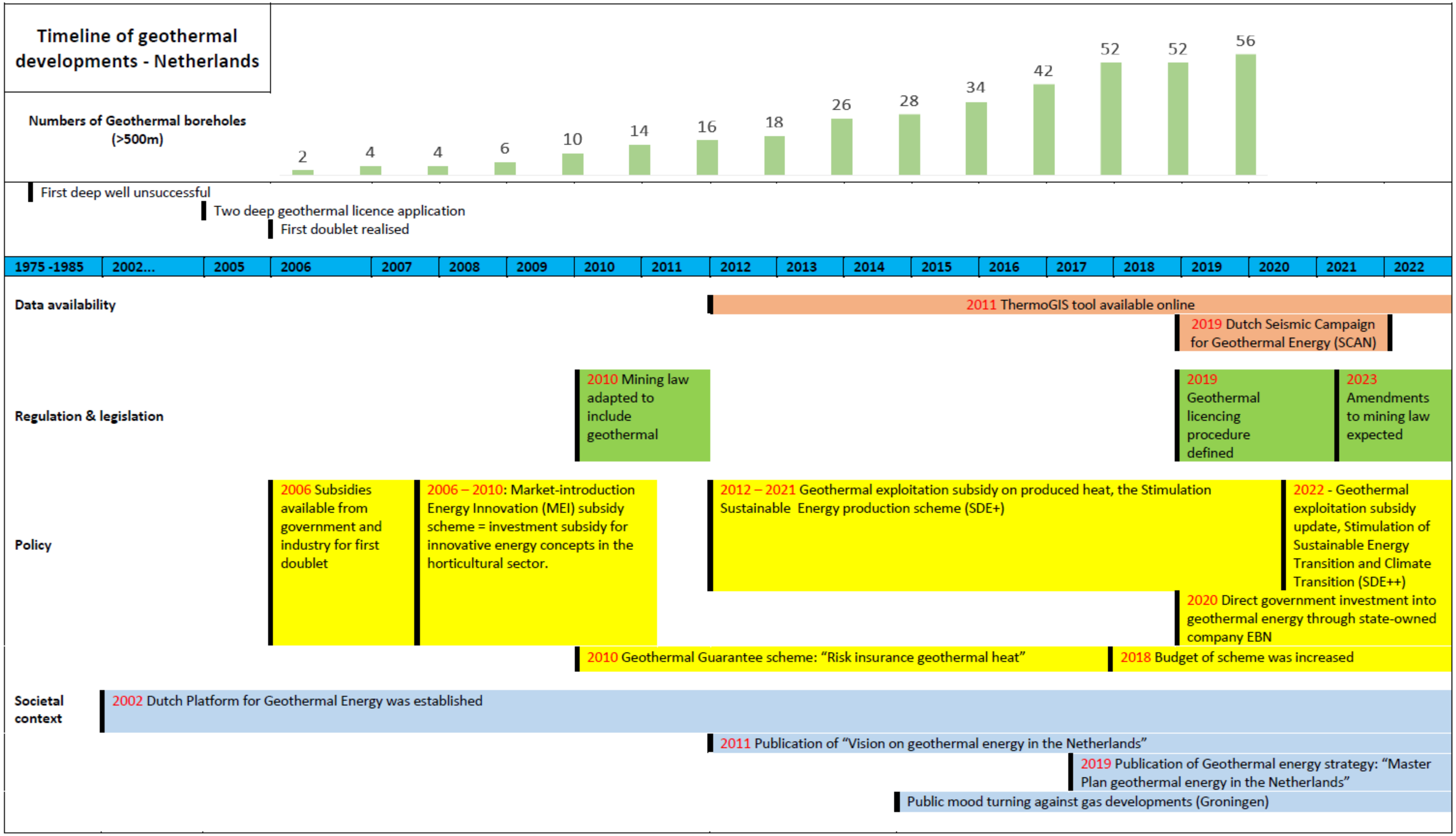
A timeline of geothermal policy developments in the Netherlands is shown in Figure 7. It highlights the long-term availability of data (e.g., ThermoGIS and SCAN) and government support (e.g., various subsidy and risk guarantee schemes). ThermoGIS[63] is developed and maintained by the Geological Survey of the Netherlands (GSN – TNO) with funding from the EU and the Dutch Government. SCAN is funded by the Dutch Government and executed by GSN-TNO and EBN.

The Netherlands have adopted the pragmatic approach of developing regulations as the industry develops,[75] resulting in regular revision and amendments to regulation and legislation (Box 3). Regulation of mining activities (including geothermal energy) are the responsibility of the Ministry of Economic Affairs and Climate (MEAC).

Various policy mechanisms have been put in place to support the country's geothermal ambition, including the Stimulation Sustainable Energy production scheme (SDE+) (which was introduced in 2012 and updated to the SDE++ in 2022) and the government guarantee scheme on drilling risks (introduced in 2010). The schemes are commissioned by MEAC and administered by the Netherlands Enterprise Agency (RVO). These policies are considered a key component in the success of deep geothermal development in the Netherlands[72] (Box 3).

In 2018, the budget of the geothermal guarantee scheme was increased to boost the number of new projects from roughly two doublets per year to five. While the scheme is reported to have increased capacity and production levels of new plants, the efforts to increase the number of schemes were frustrated by financing difficulties and slow permitting. [76] The very long permitting process has been described by the industry as putting projects at risk of losing their funding, because of waning confidence from investors and suppliers. The industry also highlights the risk that projects may not be executed in time for the SDE deadline because of delayed granting of permits. This should be remediated by the new Mining Act that will come into effect in 2023 (see Box 3).

[72] Mijnlieff, H. et al. (2013). Geothermal energy and support schemes in The Netherlands. European Geothermal Congress, Pisa, Italy.
[73] Provoost, M. et al., (2019). Country Update for The Netherlands. European Geothermal Congress Den Haag, The Netherlands.
[74] Platform Geothermie (2018). Master Plan Geothermal Energy in the Netherlands.
[75] Mijnlieff, H. personal communication 2022.
[76] Provoost, M. et al., (2019). Country Update for The Netherlands. European Geothermal Congress Den Haag, The Netherlands.



Sources: Mijnlieff et al. 2013; Bakema 2016; Van Heekeren et al. 2010; Sanner, 2019; ThermoGIS website: https://www.thermogis.nl/en/current-situation-netherlands

Figure 7:Timeline of geothermal development in the Netherlands (from Arup & BGS, © Crown copyright 2022).[14]

2.7 REGULATION AND LICENSING

Geothermal energy is recognised as a natural resource in most of the countries reviewed here. Where existing legal definitions did not include geothermal energy, legislation was amended, or new regulation passed that defines geothermal heat as a natural resource with clear rules of ownership, regulations, and licensing arrangements. In the Netherlands, for example, the resource is owned by the state, but exploration and exploitation activities generally require authorisation from the private landowner.[77] In Switzerland, there is no national geothermal legislation. In the absence of a national legal framework, several regions (cantons) have modified their mining laws to include geothermal to enable regulation and licensing for exploitation and exploration of deep geothermal resources.[78] Defining permitting and licensing frameworks for deep geothermal is regarded as an important step to provide confidence to financers and developers of deep geothermal projects[79] as well as to regulators.

Licensing arrangements in the different countries typically involve two licences, one for exploration and one for exploitation (production), which is also the case for UK hydrocarbon licences. The licensing duration ranges between one to six years for exploration licences and around 30 years for exploitation licences. Licensing authorities vary between countries, typically involving national level or regional level authorities who issue the licences but seek input and expertise from several other regulators and agencies. In addition to security for developers and investors, licensing provides the framework within which geothermal can safely be produced with minimal damage to the environment. The regulator often requires operators to meet several monitoring and reporting conditions concerning the geothermal site and wells. Additional conditions with respect to monitoring, reporting, research, risk mitigation measures and/or data sharing can be imposed with the licence.

Box 3: Geothermal Licensing in the Netherlands.

Geothermal Licensing in the Netherlands under the Mining Act 2023

In the Netherlands, a new Mining Act for geothermal energy has been adopted which is expected to come into force in the second quarter of 2023. Under the new law, exploration and extraction permits will be replaced by three permits:

- Area allocation permit (1+1 years) an initial assessment of feasibility of site and planned extraction.
- Start-up permit (2+1 years) allows the operator to investigate and develop the heat resource and some initial production.
- Follow-up permit (30 + years) - will be granted once more certainty exists on the environmental and safety impacts of the extraction and on the amount of available recoverable heat.

The new licensing regimes defines a more explicit link to the region where the exploitation takes place. As a result, municipalities and provinces will have more influence on many aspects of the geothermal development, including safety, environmental impacts and provision of information to the public. The licensing process is coordinated by the Ministry of Economic Affairs and Climate (EZK) which seeks input from different regulators and agencies during the different licensing stages, including the province, municipality and water board, the Supervision of Mines Authority (SodM), the Mining Council (Mijnraad), the Dutch Geological Survey (TNO) and the Netherlands Enterprise Agency (RVO).

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[77] Borović, S., et al. (2021). HotLime Partners' Legislation Synopsis. GeoERA
[78] Link, K. & Minnig, C. (2022). Geothermal Energy Use, Country Update for Switzerland. European Geothermal Congress 2022, Berlin, Germany | 17-21 October 2022.
[79] VITO (2020). The Balmatt project and bringing geothermal to Belgium. TWI blog 24 January 2022.

2.8 FINANCIAL SUPPORT AND RISK SHARING

Different support mechanisms are in place for geothermal projects. Here, we focus on policy mechanisms/ incentives available at national level. In many countries, these are complemented by support from administration at the regional level. Figure 8 highlights the various support scheme options that are utilised by the European countries considered in this review. An overview of the available geothermal regulations and policy mechanisms in selected European countries is given in Table 2. Direct support measures for geothermal energy are either related to project (typically CAPEX) costs (investment-based schemes) or to the actual generation of energy (heat/power) by a project (production-based schemes). Indirect support measures include taxation (e.g. carbon tax), funding for research and development (R&D) projects (e.g. technology demonstrators), or legislative measures (e.g. fossil fuel ban for new buildings).

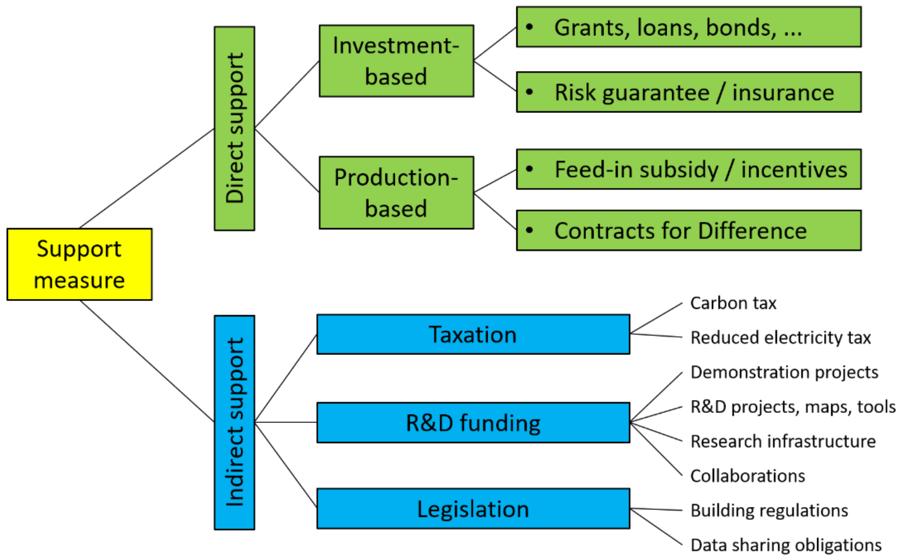

Figure 8: Support measures to develop geothermal energy deployment (BGS © UKRI 2023).

2.8.1 Direct measures

Switzerland is the only country offering **grants** for deep geothermal projects. Grants cover 60% of eligible cost for geothermal power and direct-use projects, which constitute some level of risk insurance to the project and investors. Germany is the only country that offers a loan for the cost of drilling and plant construction. Extra costs arising from unexpected drilling (e.g., for deepening a well where yields have not been achieved) can be covered as part of this loan, hence combining project financing via a loan with the mitigation of risk.[80]

Risk insurances/ guarantee schemes are available in all countries reviewed here (see Table 2), except for Germany where risk mitigation measures are part of a geothermal loan scheme. Generally, these schemes are seen as having encouraged geothermal developments in the respective countries, especially at the early development stages when drilling risks, reservoir characteristics and business models are largely unknown. France is the only country in this review to offer risk mitigation funds for the drilling and the operational stage of deep geothermal projects (see Box 4).

Feed-in Tariffs/premiums are available in all reviewed countries except for Belgium. These are regarded as a successful mechanism for supporting and rewarding successful geothermal developments. In the Netherlands, subsidy rates, aimed at compensating renewable schemes for the “unprofitable component” of their operation, are set according to

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[80] Boissavy, C. (2020). Report reviewing existing insurance schemes for geothermal, GEORISK.

the level of CO_2 reduction that a technology can achieve, and paid on the basis of emission savings (€/tonne CO_2) rather than for the amount of renewable energy produced.

We have not found any details of **Contracts for Difference (CfD)** in the context of geothermal energy in the countries reviewed in this study. Generally, CfD is only applied to renewable or low-carbon electricity, rather than heat, unless heat is defined as a tradeable product/commodity.

Box 4: Geothermal risk insurance in France

Geothermal risk insurance in France

France is one of the pioneering countries in the development of deep geothermal district heating, with the development of the Paris Basin hydrothermal aquifer, which started in the 1980s. Since then, geothermal development has broadened to include shallow geothermal energy and geothermal power projects. Key drivers for developing the geothermal sector have been France's energy policy, including the French Energy Law 2004 as well as France's greenhouse gas reduction commitments (Kyoto Agreement, Paris Climate Agreement).

Generally, France's success of geothermal development is thought to be linked to consistent technology support (since 1980s) and city scale deployment (right market conditions) to existing district heat networks (e.g., Paris Basin). Note that drilling of new wells stopped between 1988 and 2007 when government support for drilling risk (i.e. short term) was unavailable, despite there already being a somewhat established industry.

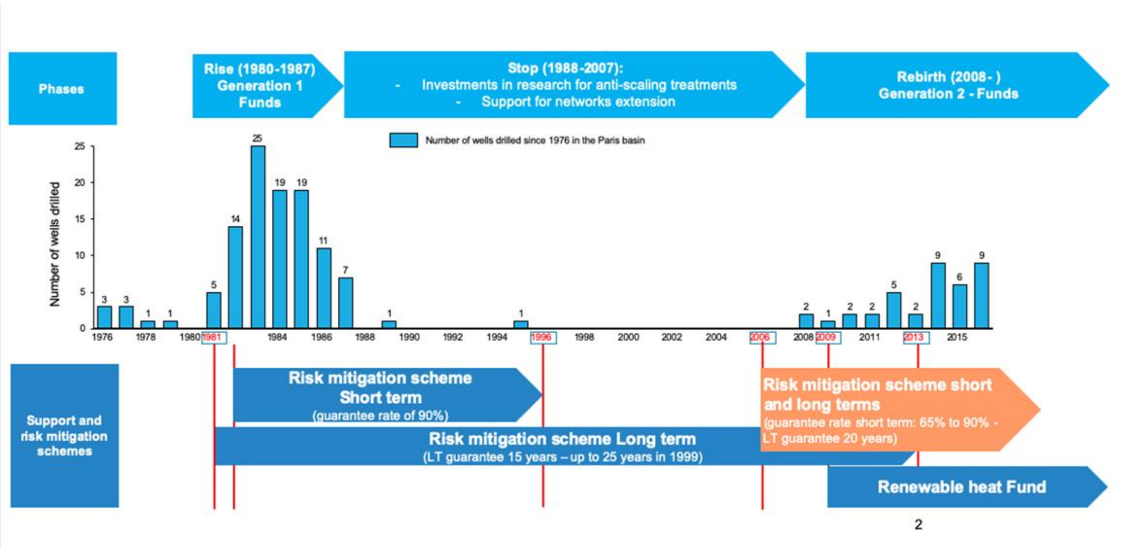

Figure 9: Risk mitigation and geothermal market development in France (Reproduced with permission © ADEME).

An illustration of how risk mitigation measures, including the short-term and long-term scheme, have contributed to geothermal success in France is shown in Figure 9 and described in detail in Boissavy (2017).[81] The fund received initial contribution from the state. This was topped up by premiums paid by the beneficiaries and by financial income arising from investing the surplus available cash. Over its lifetime, the long-term fund guaranteed investment worth €260 million for drilling and 63 geothermal operations nationwide. State payments came to €8 million, meaning that for every €1 put up by the state, €33 of an investment was covered by other income for period of 25 years.[81]

[81] Boissavy, É. C. (2017). The successful geothermal risk mitigation system in France from 1980 to 2015, European Geologist Journal, vol. 43.

2.8.2 Indirect measures

Taxation is used in some countries to encourage uptake of geothermal technologies. Tax measures include reductions in tax for the use of geothermal (e.g., Belgium) or tax penalties for generating carbon (e.g., Germany). In 2021, Germany introduced a carbon price on fossil fuel-based heating of €25 per ton of CO_2 with plans to be increased to a range of €55–65 per ton of CO_2 by 2026.[82] The EU has proposed to introduce a uniform carbon price and apply it to all 27 member states. In several countries, support for wider technology adoption is driven through **legislation** and building regulations. For example, in the Netherlands, Germany and Belgium, it is no longer permitted to install fossil fuel heating and/or connect new buildings to the gas grids.

Table 2: Comparison of geothermal regulations and policy mechanism available in the different European countries (data from ARUP & BGS, 2023[14]).

	Belgium	France	Germany	The Netherlands	United Kingdom	Switzerland
Data availability						
National Geothermal Resources tool	no	yes	yes	yes	no	no
Regulation/ Legal Framework						
Geothermal energy defined as natural resource	yes	yes	yes	yes	no	yes**
Regulation deep geothermal energy	Flemish Decree*	Mining Code	Federal Mining Act	Mining Act	/	Mining Law**
- Licence for exploration	yes	yes	yes	yes	no	yes**
- Licence for exploitation	yes	yes	yes	yes	no	yes**
- Licensing authority	R	R/N	N	N	no	R
Sharing obligation for exploration data	no	no	yes	yes	no	yes
Policy						
Investment support, loans and grants	no	no	yes	no	no	yes
Feed-in Tariffs/premiums	no	yes	yes	yes	no	yes
Contracts for Difference	no	no	no	no	yes	no
Insurance/ guarantee schemes	yes	yes	no	yes	no	yes
Research and innovation funding	no	yes	yes	yes	yes	yes
Resource assessment tool/GIS/maps	no	yes	yes	yes	no	yes
Tax benefits or penalties; carbon tax	yes	no	yes	yes	yes	no
Legislative support (e.g., building regulations)	yes	no	yes	yes	no	no

Legend: *no = not available, yes = available, * only applies in Flanders; **only for some regions, R - Regional; N – National.*

[82] Wettengel (2022). Germany's carbon pricing system for transport and buildings. Clean Energy Wire

2.8.3 Research and knowledge exchange

All countries reviewed in this study offer research support for geothermal projects. In some countries, this includes funding for pilot and demonstration projects (Germany) or large-scale collection of seismic data (Netherlands, Germany). Such projects are believed to be of enormous benefit for developing the sector as they reduce risk and uncertainty around subsurface properties, reservoir characteristics and costs. All the countries in this review participate in EU funded research projects.

3 UK geothermal potential

3.1 OVERVIEW

Most of the UK's onshore deep geothermal potential is found in deep sedimentary basins which are dispersed across the UK (Figure 11). In addition, granites found in Cornwall, the North of England, Scotland and Northern Ireland have been identified as potential geothermal targets for power and/or heat production.

Deep sedimentary basins typically contain deeply buried limestones and sandstones. Where groundwater circulation occurs within the deeply buried rocks (1–3 km), they form hydrothermal systems or deep geothermal aquifers (also called hot sedimentary aquifers). Hydrothermal systems arise from a combination of three geological components: fluid, heat and permeable rocks. Temperatures within the basins are generally 40–60°C but could reach 100°C or more in the deepest parts of some of the basins.[83] This temperature range makes these systems most suited for geothermal heating applications such as district heat networks, horticulture and industry. These hot sedimentary aquifers have large geothermal heat potential. They are also present offshore in deep sedimentary basins of the UK Continental Shelf (e.g. Jones, 2020[84]). However, offshore potential has not been included in this study.

The UK has a large theoretical potential for geothermal power generation of 357,197 EJ.[85] This is an estimate of 'the physically usable energy supply'. It does not consider technical or financial viability. Commercial project development to date focuses on regions where temperatures of more than 150ºC can be reached at depth of around 5 km or less. Drilling to deeper depth is currently not economically viable. In the UK, these temperatures are only found at economically drillable depths of 4–5 km in areas of radiogenic granites whose distribution is shown in Figure 11.

Granites, typically, are tight rocks, that have little ability to store or transport water, except where the rocks are naturally faulted or fractured. They can contain a higher proportion of radioactive elements than other rock types. Where heat from the decay of these elements accumulates within the rocks, these radiogenic granites form so called "Hot Dry Rock" (HDR) systems and are a target for geothermal energy exploitation. Some granites found in Cornwall, the North of England, Scotland and Northern Ireland have been identified as potential geothermal targets. Temperatures within these rocks are estimated to reach up to 200°C at 5 km depth – sufficient for geothermal power generation. Recent drilling to about 5 km depth in Cornwall has confirmed that such temperatures can be achieved in the granites of South West England. Drilling to shallower depths into some granites in Northern England has confirmed an above-average temperature gradient within these rocks. The geothermal potential of the granites in other areas is subject to higher uncertainty due to a lack of data. With current drilling technologies and typical funding models, the radiogenic granites are considered the only systems in the UK that potentially can produce sufficiently high temperatures for geothermal power generation.

In areas like Cornwall, where temperatures are high enough for electricity generation, geothermal energy can be fed into and distributed via the national electricity grid. This can be especially important in areas where the grid is distal to major power stations.

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[83] Busby, J. P. (2014). Geothermal energy in sedimentary basins in the UK, Hydrogeology Journal, vol. 22, pp. 129–141.
[84] Jones (2020) Offshore data availability for Carboniferous limestone in the assessment for deep geothermal energy in the UK Southern North Sea, Q47-48. British Geological Survey Internal Report, IR/20/002. 23pp.
[85] Busby, J. & Terrington, R. (2017). Assessment of the resource base for engineered geothermal systems in Great Britain, Geothermal Energy, vol. 5, 7.

3.2 UK GEOTHERMAL ENERGY PROGRAMME

The geothermal potential of the UK was investigated by a program funded by the UK government and the European Commission that ran from 1977–1994. It was initiated in response to the 1970s oil crisis. It comprised three elements: an appraisal of heat flow, an investigation of the potential of deep sedimentary aquifers to supply geothermal energy for electricity generation or direct use applications, and an investigation of radiothermal granites that might be exploited as Hot Dry Rock (HDR) reservoirs. This study was able to appraise the information available from hydrocarbon exploration and funded the drilling of seven deep geothermal boreholes, three of them drilled at Rosemanowes,[86] Cornwall, targeting the granites (at 2.6 km depth). The other four boreholes were drilled in the deep sedimentary basins at Southampton and Marchwood (Hampshire), Cleethorpes (Lincolnshire) and Larne (Northern Ireland). All, except the Southampton borehole, reached depths of more than 2 km.

The results of the programme have been summarised in Downing and Gray (1986a, b)[87,88], BGS (1988)[89], Parker (1989, 1999)[90,91] and Barker et al. (2000).[92]

The main results of the programme have been the identification of areas particularly favourable for low temperature exploration. It concluded that geothermal energy represents a significant energy source in the UK and "could provide local energy supplements given the right economic conditions and the development of an appropriate industrial base". It quantified the geothermal potential in general terms but highlighted that data from exploration and development are required to derive a realistic assessment of the available, economically-recoverable resource "for the performance of a reservoir only becomes apparent after production starts". Economic viability is also a function of the technologies available to exploit the resources and the economics of developing it compared with the cost of alternative energy sources. [87] HDR was still at an early stage of development and technical uncertainties were seen to make it unlikely that the technology would attract private sector funding in the foreseeable future.[86] Research efforts were therefore transferred to participation in the joint European Geothermal Project at Soultz-sous-Forêts.

Since then, there has not been a comprehensive review of the geothermal potential of the UK, but a number of studies have upgraded the initial estimates[83,93,94] and/or re-mapped some of the geothermal prospects[85,95] using new data that have become available since the initial assessment.

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[86] MacDonald, P. et al (1992). The UK Geothermal Hot Dry Rock programme.
[87] Downing, R. A. & Gray, D. A. (eds) (1986a). Geothermal energy: the potential in the United Kingdom. HMSO, London.
[88] Downing, R. A. & Gray, D. A. (1986b). Geothermal resources of the United Kingdom. Journal of the Geological Society, London, vol. 143, pp.499–507.
[89] BGS (1988). Geothermal Energy in the United Kingdom: review of the British Geological Survey's Program 1984–1987. British Geological Survey, Keyworth.
[90] Parker, R. H. (1989). Hot Dry Rock geothermal energy. Phase 2B Final Report of the Camborne School of Mines project, Volumes 1 and 2. Pergamon, Oxford.
[91] Parker, R. H. (1999). The Rosemanowes HDR Project 1983–1991. Geothermics, vol. 28, pp. 603–615.
[92] Barker, J. A. et al. (2000). Hydrogeothermal studies in the United Kingdom, Quarterly Journal of Engineering Geology and Hydrogeology), vol. 33, p. 41.
[93] Rollin, K. E. et al. (1995). Atlas of geothermal resources in Europe: UK revision. Technical report WK/95/07, British Geological Survey, Keyworth, UK
[94] Pasquali, R. et al. (2010). The geothermal potential of Northern Ireland. Proceedings World Geothermal Congress 2010, Bali, Indonesia, 25–29 April 2010
[95] Jones, D. et al. (2023). Deep Geothermal Resource Assessment of Early Carboniferous Limestones for Central and Southern Great Britain.

3.3 DATA AVAILABILITY

Data availability varies across the UK. Traditionally, much of the onshore geophysical and borehole data were acquired by coal mining and hydrocarbons industries. Such data is needed for defining the geometry and properties of the prospective geothermal reservoir and identifying geological structure prior to drilling. Many of these onshore seismic reflection datasets are available for purchase (for commercial users) from the UK Onshore Geophysical Library (UKOGL).

Openly available seismic and borehole data > 500 m drilled depth for the UK is shown in Figure 10. UKOGL provides index information and key picks of the available well data in Great Britain. Previously, the onshore hydrocarbon well data had to be bought from data release agents but recently BGS has released its holdings of the onshore well dataset. The data is now available through BGS GeoIndex (https://www.bgs.ac.uk/map-viewers/geoindex-onshore/), the 'Onshore UK Hydrocarbon Well Data' layer; or from searching the National Geoscience Data Centre with a well name (https://webapps.bgs.ac.uk/services/ngdc/accessions/index.html). Data for Northern Ireland is held by the Geological Survey of Northern Ireland (GSNI) and can be requested by contacting the survey (https://www2.bgs.ac.uk/gsni/).

In addition, BGS holds a comprehensive database of temperature, heat flow, thermal conductivity and geochemistry. Its latest revision (Rollin 1987,[96] available in print format only) of the UK Geothermal Catalogue (UKGC) contains over 3000 temperatures at over 1216 sites and over 200 observations of heat flow. However, about 93% of the temperature data is from depths less than 2,000 m,[97] highlighting that our knowledge of the temperature field at depth > 2 km is still very limited. This dataset is not currently publicly available.

The potential maps and assessments (below) are the output from past and current BGS research which has focussed on the assessment of UK geothermal potential, including the delineation of the UK sedimentary basins and the geothermal modelling of temperatures and potential. The research draws on a range of data sources, including those mentioned above. The methodology of how these maps were derived is not described here as details of these studies are available in reports[87,89,90,96,98] and the peer reviewed literature.[88,91,95,97]

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[96] Rollin, K. E. (1987). Catalogue of geothermal data for the land area of the United Kingdom. Third revision: April 1987. Investigation of the Geothermal Potential of the UK, British Geological Survey, Keyworth.

[97] Rollin K. E. (1995). A simple heat-flow quality function and appraisal of heat-flow measurements and heat-flow estimates from the UK Geothermal Catalogue. Tectonophysics, vol. 244, pp. 185–196

[98] Jones, D. et al. (2020). Phase 1 - resource assessment of the deep geothermal potential of UK Carboniferous Basins. British Geological Survey Internal Report, IR/21/007. 18 pp.

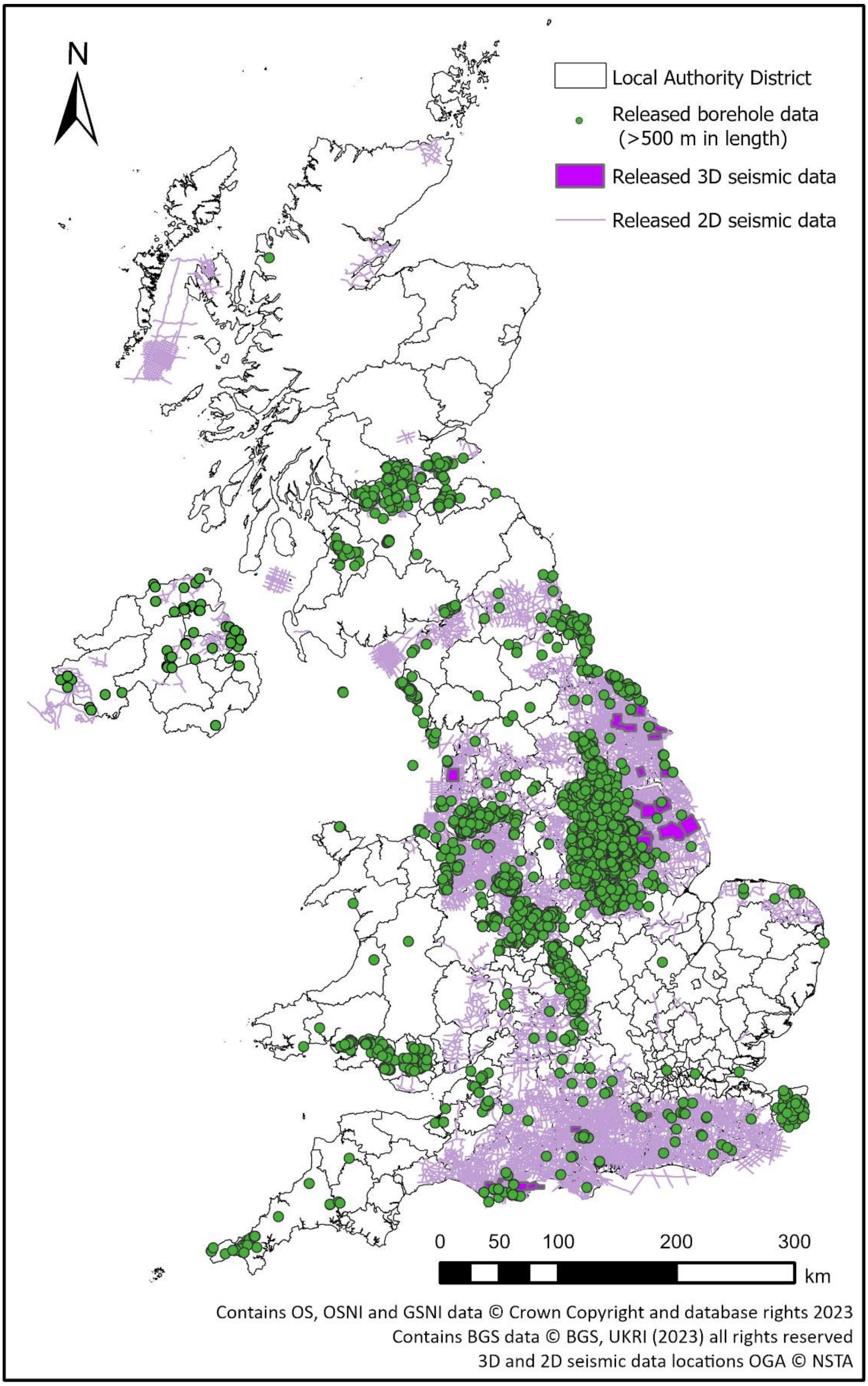

Figure 10: Map showing availability of openly accessible subsurface data at depths greater than 500m across the UK. Sources: GB data shown include borehole data (classed as non-confidential) from the British Geological Survey Single Onshore Borehole Index (SOBI- https://www.bgs.ac.uk/datasets/boreholes-index/) queried to equal or greater than 500 m. The 3D and 2D seismic data locations refer to data released by the Oil and Gas Authority (now North Sea Transition Authority) in 2017. Seismic data, well composites, formation tops and reports can be obtained from the UK Onshore Geophysical Library (https://ukogl.org.uk/map) but may need to be purchased. Northern Ireland data are available from GSNI. (BGS © UKRI 2023).

3.3.1 Geothermal exploratory boreholes

A total of 12 exploratory wells (ranging from 400 m to 2600 in depth) have been drilled in the UK specifically for deep geothermal exploration (Figure 11, Appendix 1). Seven of these deep boreholes were drilled as part of the geothermal research program in different parts of the UK (see section 5.2 UK Geothermal Energy Programme). In the 2000s, another three boreholes were drilled in the Northeast of England. These comprised two boreholes at Eastgate drilled to a depth of 995 m and 411 m into the fractured Weardale Granite and a third borehole in Newcastle (the Helix/Science Central borehole), drilled to a depth of 1,821 m, targeting the Fell Sandstone, which is now under re-evaluation (see Section 3.7.2). In 2009, two geothermal boreholes were drilled in Northern Ireland to depths of 868 m into the Sherwood Sandstone Group (Kilroot GT-01) and 601 m into the Mourne Granite (Silent Valley GT-02) as part of a deep geothermal project run by the Geological Survey of Northern Ireland. Since then, an additional four deep wells (including the two in United Downs) (400m to > 5km in depth) have been drilled for commercial exploitation in the UK. Further information relating to these boreholes are included in Appendix 1.

3.4 GEOTHERMAL PROSPECTS

Potential geothermal targets occur in different geological settings across the UK (Figure 11). They differ in terms of the geological structures and heat flows, age and types of rocks, and the way water moves through these rocks. In Figure 11, three types of geothermal prospects are mapped:

3.4.1 Hot sedimentary aquifers

As previously defined in Section 1.3, hot sedimentary aquifers (HSA) are permeable rocks of sedimentary origin that contain water at elevated temperatures. They occur in the deep sedimentary basins across the UK. Water flows either in the rock matrix or through fractures or faults. In the context of this report, the term HSA is used to refer to the sedimentary basins of Permian and Triassic age, which largely contain porous sandstones. Fluid flow is predominantly through the porous and permeable rock matrix. Where fractures and faults are present, these may enhance the water flow within these aquifers.

Hot sedimentary aquifers in the UK include the Triassic Sherwood Sandstone Group (SSG); the Permian Bridgnorth Sandstone (BS) and the Collyhurst Sandstone (CS) formations which make up the main geothermal targets within the basins that formed in Permian to Early Mesozoic times (shown in yellow in Figure 11) as well as the Carboniferous Fell Sandstone Formation (shown within the blue in Figure 11). Additionally, several less prominent Carboniferous (blue) and Permian (yellow) sandstones are also present beneath the Sherwood Sandstone Group within basins in Northern Ireland.

3.4.2 Fractured sedimentary aquifers

Fractured sedimentary aquifers are a sub-type of Hot Sedimentary Aquifer, typically consisting of limestones or tight sandstones (i.e., where the rock matrix is not conducive to water flow). These systems rely on fractures and faults for transporting water, and in limestones on karstification –where the rocks have been dissolved by natural processes to create cavities and solution-enhanced fractures through which water can flow.

Fractured sedimentary aquifers in the UK include the Carboniferous Limestone Supergroup as well as the Devonian–Carboniferous sandstones of the Midland Valley of Scotland which are the main targets in the pre-Permian basins (shown in blue in Figure 11).

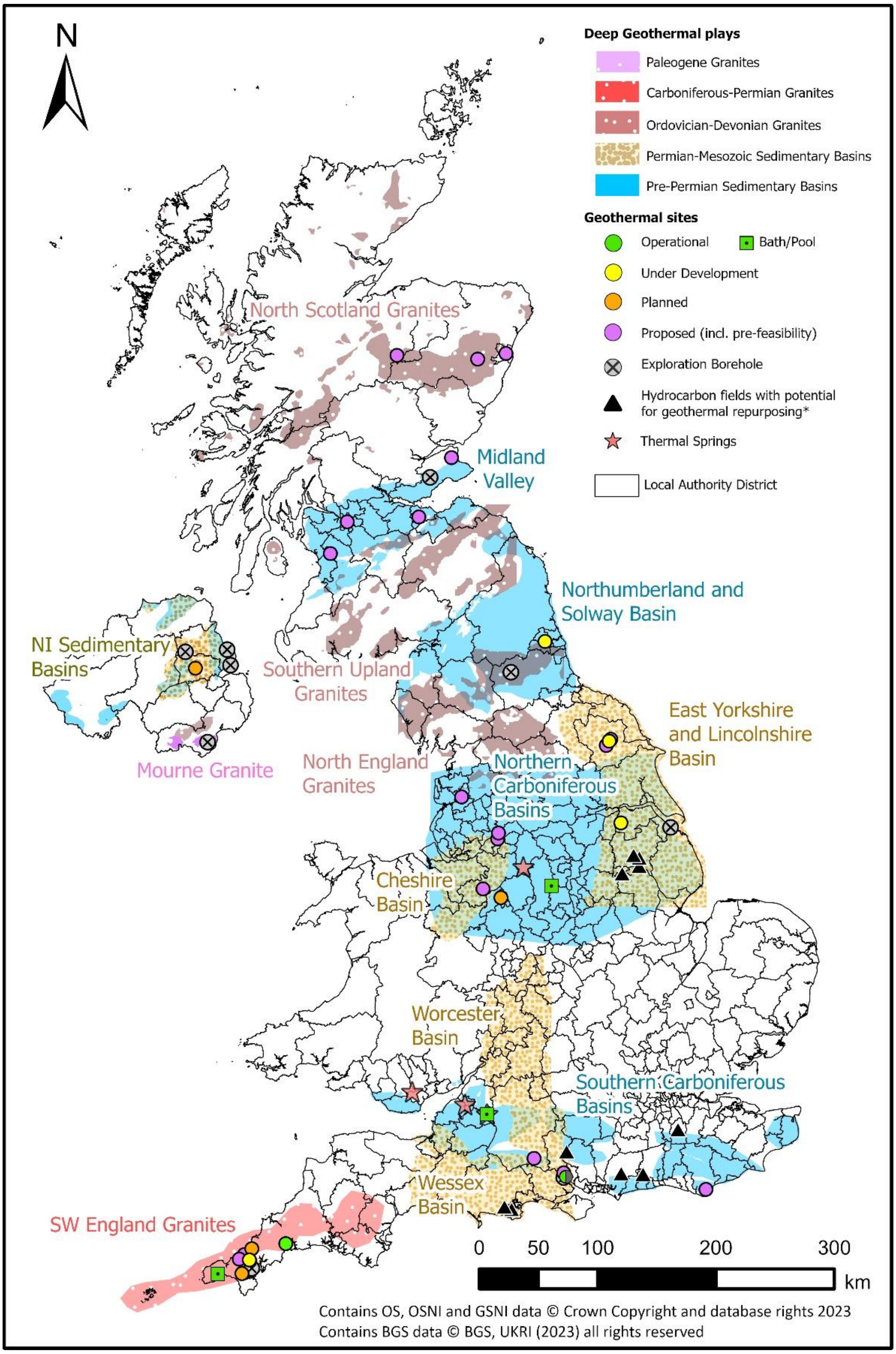

Figure 11: Map showing the location of the potential deep geothermal targets across the UK alongside selected onshore hydrocarbon fields (triangles), occurrences of known thermal springs (stars) and geothermal projects at different stages of development from pre-feasibility to operational (See Appendix 1 for data sources). Southampton is shown as part-operational to highlight that it is not currently operational and was initially drilled as an exploratory borehole. Note that the map only shows the extent of the geothermal basins / granite intrusions. There is great variability in terms of reservoir properties and temperatures within individual basins as well as drillability of the (overlying) rocks. More detailed site-specific studies and investigations are required to confirm feasibility for geothermal exploitation of a site/area (See Project Road Map in Appendix 4). (© North East LEP).

3.4.3 Radiothermal granites

Some granites, compared to other rock types, contain a higher proportion of radioactive elements. Although the overall concentrations of these elements in the rock are small, their decay generates heat which builds up, naturally heating the rocks. Typically, granites are tight rocks, i.e., the rocks have little ability to store or transport water (i.e., low porosity and permeability), and hence these systems are classed as “Hot Dry Rocks”. Water flow within the granites, where it occurs, is limited to natural faults and fracture systems, which form the main targets for geothermal exploitation. With current drilling technologies, these systems are considered the only systems in the UK that are hot enough for geothermal power generation.

Their naturally low permeability means that the flow pathways within the rocks may need to be enhanced or created through artificial stimulation (hydraulic fracturing or acidification) to enable utilisation of the energy. Therefore, geothermal development targeting these radiogenic granites in the UK are generally considered to be Enhanced Geothermal Systems. Granites of Permian age (shown in red in Figure 11) in the SW of England, are the main target for geothermal development of this type in the UK at present, but Ordovician / Devonian granites (shown in brown in Figure 11) and Paleogene granites (shown in purple in Figure 11) elsewhere in the UK may also have potential. As drilling technologies improve, future exploration targets may include the deep crystalline basement rocks at depths of 7 km or more.

3.4.4 Heat in place

The Inferred Geothermal Potential (as defined in the UNFC classification) (also called heat in place) has been assessed for the main sedimentary basins in the UK, where there are sufficient data, and is summarised in Table 3. Estimates of the geothermal potential are not yet available for the Midland Valley of Scotland which is currently being assessed in a study undertaken by the British Geological Survey. They are expected to become available later in 2023.

Heat in place is all heat that is stored within the sedimentary basins. Only a small fraction of this heat is accessible. Estimation of the identified, economically useable fraction requires more detailed knowledge of the deep subsurface, which is usually obtained through targeted exploration (e.g. geophysical surveys and drilling). The economically recoverable fraction is also dependent on technology developments and costs. New drilling technologies that enable cheaper and deeper drilling, for example, could make more of the heat in place accessible and economically useable, hence increasing the geothermal resource (see Section 4.7).

3.4.5 Geothermal power potential

The geothermal heat and power potential of the radiothermal granites is believed to be high but estimates of heat in place are not available. However, Busby and Terrington (2017)[85] calculated a technical potential for geothermal power generation of 2,280 MW_e for the radiothermal granites of the UK, assuming drilling depths to ~5 km and operational temperatures of ~200°C. In their study, the technical potential is defined as ‘the fraction of the physically accessible potential that can be used under the existing technical ...., structural and ecological restrictions as well as legal and regulatory allowances.’[99]

The availability of an accessible geothermal source within the granites of Cornwall was demonstrated by the United Downs Deep Geothermal Power (UDDGP) project in Cornwall, which observed bottomhole temperatures of 200°C at 5 km depth. Prior to that, the three wells at Rosemanowes, drilled as part of the UK Geothermal Energy Programme, observed

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[99] Beardsmore GR, Rybach L, Blackwell D, Baron C. (2010) A protocol for estimating and mapping global EGS potential. Geothermal Resource Council Trans. 34, pp. 301–312.

bottomhole temperatures of around 100°C at depth of 2.6 km within the Cornubian granites.[100]

Table 3. Heat in place estimations for the Permian – Mesozoic basins obtained by Rollin et al. (1995)[101] for England and by Downing and Gray (1986)[102] for Northern Ireland (available in Busby (2014)[103]), for the Carboniferous Limestones by Jones et al. (2023)[95] and for the Fell Sandstone by Sutton (2022).[104]

	Basin	Aquifer	Area (km^2)	Heat in Place (EJ)	Details in
Permian-Mesozoic Basins	Eastern England	SSG Triassic	4827	122	Figure 12B
	Wessex	SSG Triassic	4188	27	Figure 13D
	Worcester	SSG Triassic	500	8	Figure 13C
		BS Permian	1173	60	
	Cheshire	SSG Triassic	677	36	Figure 12A
		CS Permian	1266	38	
	Northern Ireland	SSG Triassic	1618	35	
	Total heat in place in Permian-Mesozoic Basins			**326**	
Pre-Permian Basins	Northern Province	Carboniferous Limestones	~30,000	1,278	Figure 15G
	Southern Province	Carboniferous Limestones	2179	186	Figure 15H
	NE England	Fell Sandstone	1931	1.6	Figure 14F
	Midland Valley Scotland	Upper Devonian and Carboniferous Sandstones-		Not available	Figure 14E
	Total heat in place in Pre-Permian Basins			**1,465.6**	

The Rookhope[105] and Eastgate[106] boreholes, drilled in 1961 and 2004 (Eastgate 1) into the Weardale Granite (N England), encountered bottomhole temperatures of 40°C and 46.2°C at depth of 800 m and 995 m, respectively. At an average UK geothermal gradient of 26°C/km, temperatures at those depths would typically be expected to be around 30–36°C. A second borehole at the Eastgate site (Eastgate-2) was drilled in 2010 to a depth of 420 m to investigate the lateral continuity of the fractures.[107]

[100] Richards, H. G. et al. (1994). The performance and characteristics of the experimental hot dry rock geothermal reservoir at Rosemanowes, Cornwall (1985–1988). Geothermics, vol. 23, pp. 73–109.
[101] Rollin, K. E. et al. (1995). Atlas of Geothermal Resources in Europe: UK Revision. Technical Report WK/95/07, British Geological Survey, Keyworth.
[102] Downing, R. A. & Gray, D. A. (eds) (1986). Geothermal energy: the potential in the United Kingdom. HMSO, London.
[103] Busby J. P. (2014). Geothermal energy in sedimentary basins in the UK. Hydrogeol J, vol 22, pp. 129–141.
[104] Sutton, R. (2022). Assessing the Geothermal Potential of the Lower Carboniferous Fell Sandstone. Master thesis, Durham University.
[105] Dunham, K. C. et al. (1965). Granite beneath Viséan sediments with mineralization at Rookhope, northern Pennines. Quarterly Journal of the Geological Society, vol. 121), pp. 383–414.
[106] Manning, D. A. C., et al. (2007). A deep geothermal exploration well at Eastgate, Weardale, UK: a novel exploration concept for low-enthalpy resources. Journal of the Geological Society, vol. 164, pp. 371–382.
[107] Brown, C. S., & Howell, L. (2023). Unlocking deep geothermal energy in the UK using borehole heat exchangers. Geology Today, 39(2), 67-71.

The granites of Scotland and Northern Ireland may also be areas with hot dry rock potential.[108,109] However, due to limited data in these areas, their geothermal potential has not been assessed to date.

3.5 REGIONAL ASSESSMENT OF GEOTHERMAL POTENTIAL

Regional assessments of the available geothermal potential (heat in place) in the main sedimentary basins in England, Wales and Scotland are shown in Figure 12 to Figure 15. The maps are based on recent work undertaken by the British Geological Survey which included remapping and reassessment of the geothermal prospects based on new data that has become available since the initial geothermal assessment in the 1980s.[110]

The maps (left panels) show the distribution of the geothermal potential (as maximum available energy per square km expressed in PJ/km^2). Only areas that are estimated to deliver temperatures greater than 50°C are shown (which is considered as the minimum requirement for direct use). It should be noted that the colour scales differ between figures. Also shown are the depth contours (dashed lines) within the basin to the top of the geothermal aquifer or reservoir. These provide a first approximation of the anticipated minimum depth of drilling. Figure 14E shows temperature data instead of the available heat in place. An example of a conversion from heat in place (PJ/km^2) to recoverable heat (MW) is provided in Appendix 5. Note that the given values are indicative and based on several assumptions - as stated in the text.

To highlight opportunities for developing the geothermal potential in these basins, e.g., for district heating or to decarbonise the public sector estate (see Chapter 6), locations of NHS hospitals that have been prioritised by the Carbon Energy Fund[111] for decarbonisation because of their high heat demand are shown in the panels on the right along with areas identified by the Department for Energy Security and Net Zero's (previously BEIS) Second National Comprehensive Assessment[112] as having potential for heat network development.

It is important to note that these regional assessments are indicative. While some reservoir properties have been included in the heat in place calculations (see Appendix 5), the models have been parameterised with a probability distribution function[95] rather than with area- or site-specific information. Therefore, local reservoir properties and geological uncertainties have not been considered. Further analysis in the form of a site-specific or area-specific feasibility study (see Appendix 4) is required to assess viability at the site level before any drilling should take place.

[108] Busby, J. et al. (2015). How hot are the Cairngorms? Scottish Journal of Geology, vol. 51, pp. 105–115.
[109] Raine, R. J. & Reay, D. M. (2021). Geothermal energy potential in Northern Ireland: summary and recommendations for the Geothermal Advisory Committee.
[110] Downing, R. A. & Gray, D. A. (1986). Geothermal energy – the potential in the United Kingdom. BGS.
[111] https://www.carbonandenergyfund.net/
[112] BEIS (2021). Opportunity areas for district heating networks in the UK: Second National Comprehensive Assessment. UK GOV.

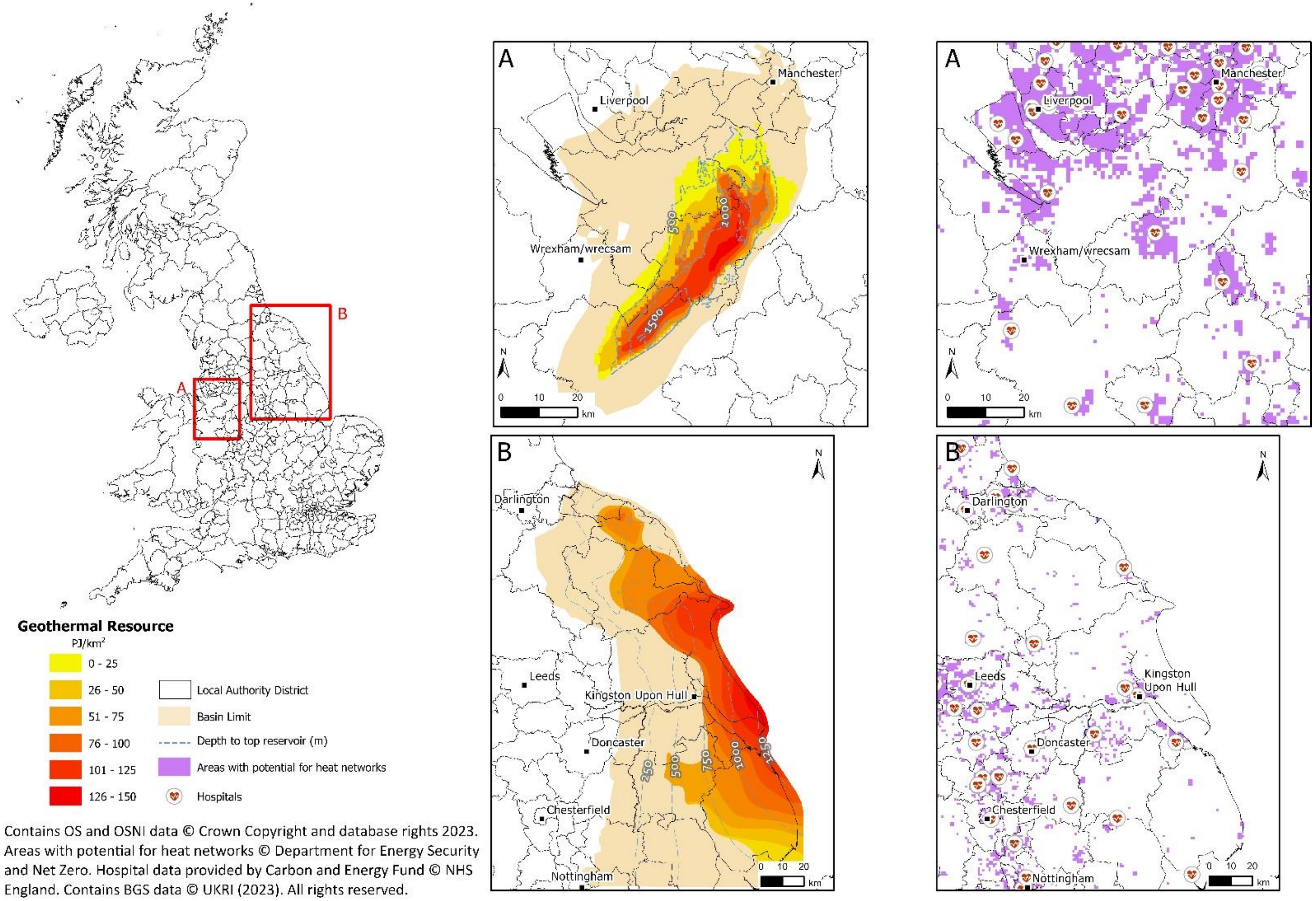


Figure 12 : Maps showing location, depth, and heat in place within assessed Mesozoic saline aquifers: (A) Cheshire Basin;(B) East Yorkshire- Lincolnshire Basin. Left panels: Heat in Place (PJ/km^2) is only shown for those parts of the basins where temperatures are expected to be > 50°C. Colours illustrates the available heat in place within the basin. Depth contours show the estimated depth to the uppermost aquifer. A conversion from heat in place (PJ/km^2) to recoverable heat (MW) is provided in Appendix 5. Right panels: Location of NHS hospitals with high heat demand and areas identified as having potential for heat network development[113] (© North East LEP).

[113] BEIS (2021). Opportunity areas for district heating networks in the UK: Second National Comprehensive Assessment. UK GOV.

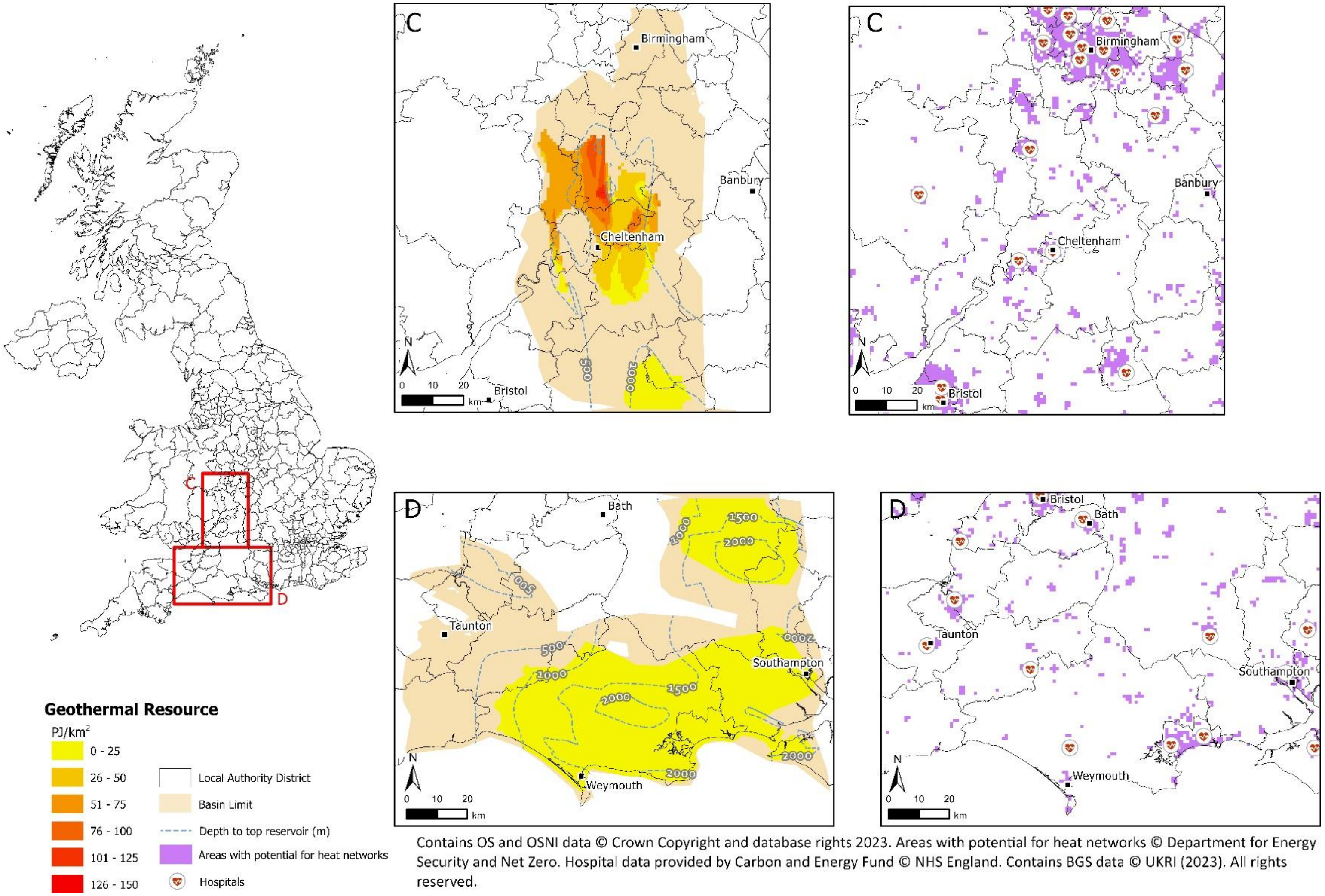


Figure 13: Map showing location, depth, and heat in place within the assessed Mesozoic saline aquifers: (C) Worcester Basin and (D) Wessex Basin. Left panels: Heat in Place (PJ/km^2) is only shown for those parts of the basins where temperatures are expected to be > 50°C. Colours illustrates the available heat in place within the basin. Depth contours show the estimated depth to the uppermost aquifer. An example of a conversion from heat in place (PJ/km^2) to recoverable heat (MW) is provided in Appendix 5. Right panels: Location of NHS hospitals with high heat demand and areas identified as having potential for heat network development[113] (© North East LEP).

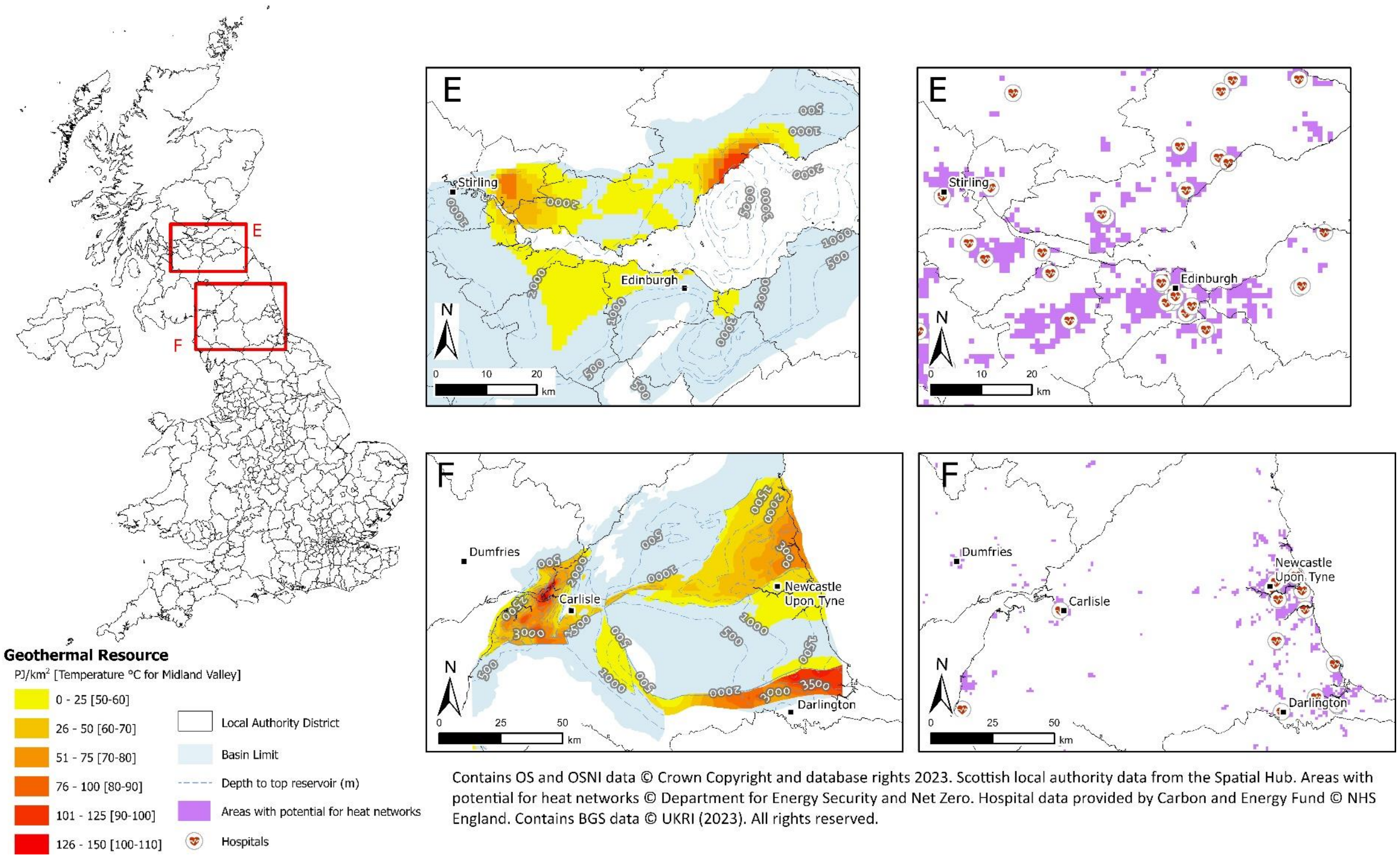


Figure 14: Map showing location, depth, and heat in place within (E) the not-assessed Midland Valley of Scotland and (F) the assessed Palaeozoic Middle Border Group in Northern England. Left panels: (E) Temperature data is shown for the Midland Valley of Scotland (as heat in place estimates not yet available). (F) Heat in Place (PJ/km^2) is only shown for those parts of the basins where temperatures are expected to be > 50°C. Colours illustrates the available heat in place within the basin. Depth contours show the estimated depth to the uppermost aquifer. An example of a conversion from heat in place (PJ/km^2) to recoverable heat (MW) is provided in Appendix 5. Right panels: Location of NHS hospitals with high heat demand and areas identified as having potential for heat network development[113] (© North East LEP).

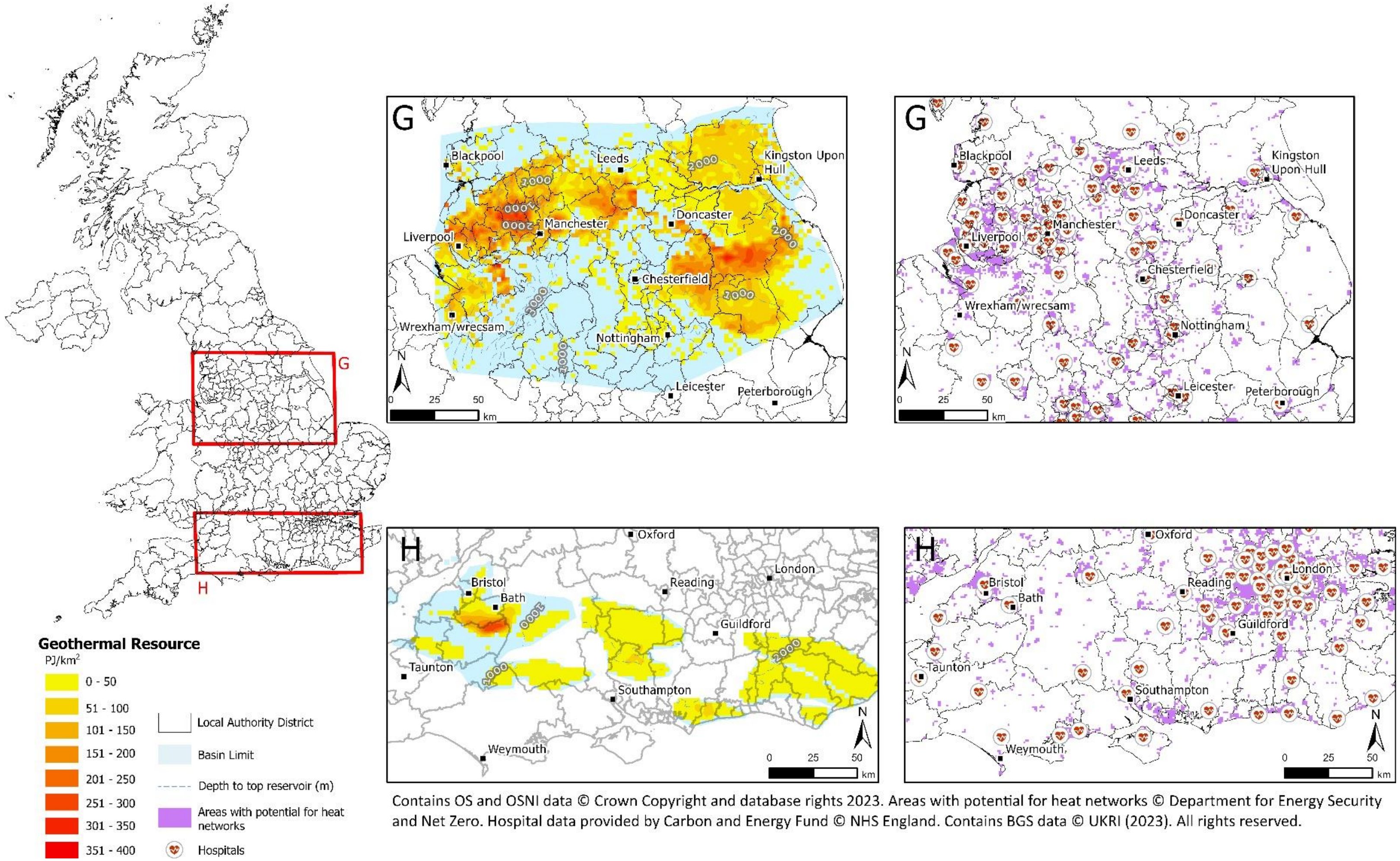
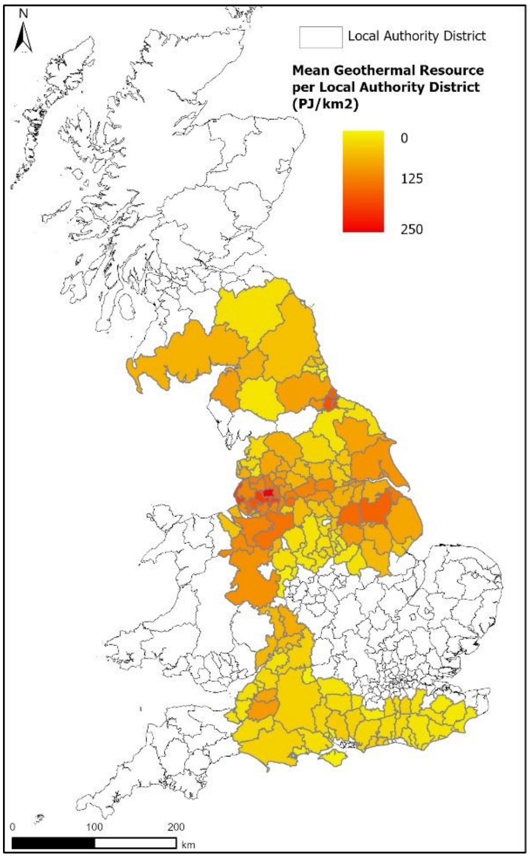


Figure 15: Map showing location, depth, and heat in place of assessed Palaeozoic Carboniferous Limestone aquifers in (G) Northern England and (H) Southern England. Left panels: Heat in Place (PJ/km^2) is only shown for those parts of the basins where temperatures are expected to be > 50°C. Colours illustrates the available heat in place within the basin. Depth contours show the estimated depth to the uppermost aquifer. An example of a conversion from heat in place (PJ/km^2) to recoverable heat (MW) is provided in Appendix 5. Right panels: Location of NHS hospitals with high heat demand and areas identified as having potential for heat network development[113] (© North East LEP).

3.6 IDENTIFICATION OF AREAS WITH POTENTIAL FOR DIRECT USE GEOTHERMAL HEATING

Using the BGS datasets described above, local authority districts that have a deep geothermal aquifer and hence a potential hot water supply at depth have been mapped as shown in Figure 16. On the left, estimates of the available heat in place averaged across each local authority district (PJ/km^2) are shown. Crudely, these estimates can be used as a crude indication of where higher temperatures may be achievable relative to adjacent areas. On the right, the estimated (vertical) depth to the topmost geothermal aquifer (averaged across the local authority district) is shown to give an indicative measure of the minimum drilling depth. Both maps are only indicative and more detailed, area-specific investigations will be needed to better constrain temperature and depth of the potential source for the areas shown here.

Averaging across the district means that the geothermal potential and depth will be underestimated in some parts of the district and overestimated in others, especially in larger districts. Where multiple geothermal aquifers intersect a local authority district, the mean heat in place values for each potential aquifer have been summed accordingly and the depths of the shallower target is shown.



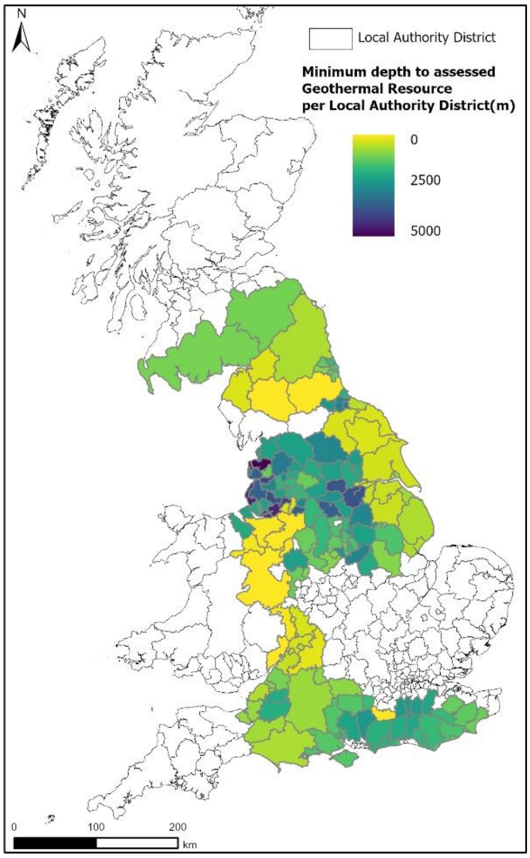


Figure 16: Map of geothermal opportunities for deep geothermal heat projects (only for sedimentary basins, granites are not included in the analysis in this figure) averaged across Local Authority Districts. Northern Ireland data not available. Left: Distribution of mean geothermal potential (PJ/km^2) per local authority district. An example of a conversion from heat in place (PJ/km^2) to recoverable heat (MW) is provided in Appendix 5. Right: Minimum depth (m) to an assessed geothermal potential averaged across local authority district. Maps were derived by extracting point data for each local authority district from the geothermal potential grids and average values across the LAD within ArcGIS pro to give a mean heat in place resource (PJ/km^2). Contains OS data © Crown Copyright and database rights 2023. Contains BGS data © BGS, UKRI (2023) all rights reserved (© North East LEP).

The figures illustrate that opportunities for deep geothermal developments exist in many parts of the UK. Although heat in place and depth estimates are only indicative, they highlight districts which can be prioritised in the development of deep geothermal energy. However, no prioritsation is made as all identified areas have potential to provide a geothermal heat source. Decisions of where and how to develop geothermal energy will depend on a number of factors that have not been considered here, including site-specific geological setting, intended use and temperature requirements. For some applications, developing a shallower lower temperature target could be equally or more cost effective than developing a deeper, higher temperature target.

3.7 PIPELINE OF DEEP GEOTHERMAL PROJECTS IN THE UK AT JULY 2023

Existing and planned deep geothermal projects are shown in Figure 11 and summarised in Appendix 1. In total, there are four operational projects, four projects in development and a further 24 projects under consideration, including three projects that have received planning permission. The following section gives a short overview of the current project pipeline in the UK. Further details and references are provided in Appendix 1.

3.7.1 Operational projects

For more than three decades, the Southampton well has been the only deep geothermal that has been operational in the UK. The well, drilled initially as an exploratory borehole, was brought into production in 1987 and connected to the city centre district heating network with an installed capacity of 1.8 MW_{th}. The brine was extracted from the Sherwood Sandstone Group (Permo-Triassic) aquifer of the Wessex Basin (Figure 13D) at a depth interval of 1,725-1,749 m and a temperature of 76°C. The used water is discharged to sea at 38°C. The well is currently not in operation.

In Cornwall, the Jubilee Pool includes a partitioned sub-section of a seawater pool that is heated with an open loop ground source heat pump supplied from a 400 m deep borehole at an inlet temperature of 25°C. Initially planned as a deep well, the project experienced some difficulties with the drilling. Warm water was encountered at shallower depth, and temperatures are boosted by a heat pump to achieve the required temperatures.

Also in Cornwall, the Eden Geothermal project, near St Austell, has drilled a first well to around 4.5 km vertical depth. They installed a coaxial system which is connected to a heat network to provide heat to the Eden Biomes facilities during the first phase of the project that went live on June 2023. The second phase will include drilling a second well and construction of a power plant to supply heat and electricity to the Biomes, greenhouses and associated facilities.

Other projects use deep geothermal sources through accessing natural hot springs. These include the Thermae Spa in Bath, and the New Bath Hotel and Spa in Matlock Bath which use geothermal waters from the Carboniferous Limestone deep geothermal system in Northern England (Figure 15H).

3.7.2 Projects under development and planned

The United Downs Deep Geothermal project in Cornwall has successfully drilled two deep boreholes into the Porthtowan Fault zone within the Cornish granites, the deeper of the two at more than 5 km depth, to provide the first geothermal power in the UK.[114] The power plant design is currently being finalised with the start of construction estimated for 2023. The plant will generate between 1 and 3 MW of electricity and 15 MW of heat. Four additional deep geothermal projects in Cornwall have been announced (Mawla, Tolvaddon, Penhallow and Manhay). The latter two have recently obtained planning permission. The design and construction of the new projects will follow the successful experience of United Downs, with two deep wells, one for abstraction at around 4,500 m depth and one for reinjection at around 3,000 m depth, producing around 5 MW_e and 20 MW_{th} each from the deep granites.

In Newcastle, the Science Central borehole is being assessed within the NetZero GeoRDIE[115] project with plans to be refurbished and developed as a co-axial well that aims to be connected to the Helix district heating network operated by EQUANS. The well has a bottomhole

[114] Farndale, H. & Law, R. (2022). An Update on the United Downs Geothermal Power Project, Cornwall, UK. In Proceedings of the 47th Workshop on Geothermal Reservoir Engineering, Stanford, CA, USA.
[115] NetZero GeoRDIE. Newcastle University.

temperature of ~70°C at 1,600 m depth but was originally not put into production due to low yields.[116]

Up to four wells will be drilled in the Sherwood Sandstone Group to a depth of approximately 500 m to provide heat to the Scunthorpe General Hospital. The system is supported by ground source heat pumps to achieve the necessary operational temperatures. Drilling of the first well was completed in 2023.

In Stoke-on-Trent, a geothermal doublet is planned to supply a district heat network in the Etruria Valley (see for details in Section 4.2.1).

In Northern Ireland, support for two geothermal demonstrators has been announced by the Department for the Economy. Initial feasibility assessments and exploratory drilling have been commissioned and will be carried out in 2023/24 on the Stormont Estate (shallow geothermal) and at the Agricultural College (CAFRE), near Antrim (deep geothermal). The deep geothermal part of the project will be used to better understand the subsurface in Northern Ireland and aims to promote geothermal uptake in the agri-food sector. The study will include geophysical surveys in and around the site and collection of subsurface data needed to assess the available resource and identify a drill site for a deep geothermal well, targeting the Sherwood Sandstone Group.

3.7.3 Proposed projects (including pre/feasibility)

Several geothermal projects have been proposed and assessed at the prefeasibility or feasibility phases. Only a limited number of them (those shown above), have progressed to the planning, construction or operational phase.

The supply of heat to large public buildings using geothermal energy is of increasing interest. A few projects to supply heat to NHS hospitals are under consideration. If realised, they could contribute to reduce carbon emissions and heating costs (see case study in Section 4.2.2).

In Scotland, three deep geothermal feasibility studies were funded by the Scottish Government Energy Challenge Fund, as part of the Low Carbon Infrastructure Transition Programme (LCITP).[117] They targeted different geological settings and technologies including an EGS study in the granites of the Hill of Fare (near Banchory, Aberdeenshire) [118], a deep single coaxial well to supply the new Aberdeen Exhibition and Conference Centre,[119] and a low enthalpy geothermal scheme as part of a district heating system in Guardbridge (Fife) targeting a permeable fault zone in the Hot Sedimentary Aquifer (consisting of Devonian sandstones and limestone).[120,121] These projects have not progressed. Reasons given,[122] include economic challenges, competition with other low-carbon sources (mainly biomass) and potential risks. A more recent project, also in Scotland, was proposed to supply heat to the Heriot-Watt University campus. The funding application was turned down and the project temporarily paused. These projects might be revived if funding becomes available.

In 2022, the intention to develop a 6 km deep geothermal borehole on the banks of the River Clyde in Glasgow has been reported, but there are currently no confirmed details regarding the location, type of system or development time scale. The Bishop Auckland Project in North East England intends to harness geothermal energy from the granites to heat Bishop Auckland Castle.[123]

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[116] Younger, P. L. et al. (2016). Geothermal exploration in the Fell Sandstone Formation (Mississippian) beneath the city centre of Newcastle upon Tyne, UK: the Newcastle Science Central deep geothermal borehole. Quarterly Journal of Engineering Geology and Hydrogeology, vol. 49, pp. 350–363.
[117] https://www.gov.scot/policies/renewable-and-low-carbon-energy/geothermal-energy/
[118] Hill of Banchory geothermal energy project: feasibility report
[119] Feasibility Report of a Deep Geothermal Single Well, Aberdeen Exhibition and Conference Centre
[120] Guardbridge geothermal technology demonstrator project: feasibility report
[121] Comerford, A. et al. (2018). Controls on geothermal heat recovery from a hot sedimentary aquifer in Guardbridge, Scotland: Field measurements, modelling and long term sustainability. Geothermics, vol. 76, 125–140.
[122] Townsend, D. et al. (2020). “On The Rocks” – Exploring Business Models for Geothermal Heat in the Land of Scotch, Proceedings World Geothermal Congress 2020, Reykjavik, Iceland, April 26 – May 2, 2020
[123] https://www.thenorthernecho.co.uk/news/23328872.bishop-auckland-centre-geothermal-expertise/#comments-anchor

The 2 km-deep Halo Kilmarnock geothermal single well was planned at a former whisky bottling site to develop Scotland's first deep geothermal district heating network.[124] It was part of a larger (£65 million) regeneration scheme and had £3.5 million and £1.8 million of grant funding support from the UK Government and the Scottish Government Low Carbon Infrastructure Transition Programme (LCITP), respectively. The project is part of the UK Industrial Strategy, but the geothermal component was abandoned in 2018 (for reasons not disclosed).

[124] https://www.thinkgeoenergy.com/urban-regeneration-project-including-geothermal-district-heating-system-kicked-off-in-scotland/

4 Opportunities for deep geothermal in the UK

This chapter outlines the opportunities for developing geothermal energy in the UK, including synergies with other sectors as well as the co-benefits that can be created by building a geothermal sector in the UK.

In 2019, the UK's Climate Change Act (2008) was amended to legislate a long-term, economy-wide target to reach net zero greenhouse gas emissions by 2050.[125] Prior to this amendment, the Act had set a target of at least 80% reduction from 1990 levels by 2050. Under the provisions of the Act, a carbon budgeting system was introduced, which provide legally binding limits on the amount of emissions that may be produced in successive five-year periods, beginning in 2008. The act also established the Climate Change Committee (CCC) - an independent body designed to recommend targets, advise on the level of carbon budgets, as well as to monitor and report progress towards targets.

The sixth carbon budget, covering the period (2033–2037), was set in law in 2021[126] and requires a 78% cut in emissions by 2035 relative to 1990, which is equivalent to a 63% reduction from 2019. Advice from the CCC on reaching the sixth carbon budget involves direct emission reductions from buildings by 17% compared to 2019 through efficiency savings and deployment of low-carbon district heating. It predicts that around 20% of UK heat will need to come from low-carbon heat networks by 2050 if the UK is to meet its carbon targets cost-effectively.[127]

While decarbonisation of electricity has made good progress over the past decade, a recent CCC progress report[128] highlights that decarbonisation of heating and hot water has barely been addressed. With less than 5% of the energy used for heating/cooling homes and buildings currently being derived from low-carbon sources, it remains the greatest decarbonisation challenge.[129]

The power and heat generated by geothermal technologies are generally low-carbon, and geothermal energy is identified in the Heat and Buildings Strategy[130] as a potential supply for low-carbon heat networks. If recognised and supported like other renewable technologies, it has potential to make an important contribution to meeting the UK's decarbonisation targets as well as to benefit related Government's agendas, including Green Growth,[131] Energy Security[132] and Levelling Up[133] – as outlined below.

4.1 STAKEHOLDER VIEWS ON GEOTHERMAL OPPORTUNITIES IN THE UK

The following section gives an overview of the main opportunities for geothermal energy in the UK. It starts with highlighting stakeholder views (see section 1.4 for the stakeholder engagement methodology), followed by a more detailed exploration of the identified opportunities and linked agendas. A summary of the stakeholder evidence is given in Appendix 2.

Stakeholders strongly agree that there is potential for developing deep geothermal in the UK, especially geothermal heat. Several applications were identified by participants of the stakeholder workshop including district heating, heat networks, domestic heating, social, commercial, and communal heating, horticulture, food production, Combined Heat and Power, heat for recreational use & wellbeing (e.g., spas, leisure facilities), geothermal cooling, thermal energy storage and co-production of heat and minerals (e.g., lithium). Beside decarbonisation

125 The Climate Change Act 2008 (2050 Target Amendment) Order 2019
126 UKGOV: The Carbon Budget Order 2021
127 CCC (2020). The Sixth Carbon Budget: The UK's path to Net Zero.
128 CCC (2020). Reducing UK emissions: 2020 Progress Report to Parliament.
129 BEIS (2021). Opportunity Areas for District heating Networks in the UK.
130 HM Government (2021). Heat and Buildings Strategy, October 2021
131 BEIS (2021). Net Zero Strategy: Build Back Greener, October 2021
132 BEIS & Prime Minister's Office (2022). British Energy Security Strategy, March 2022
133 HM Government (2022). Levelling Up the United Kingdom, Policy paper, February 2022

benefits and provision low-carbon heat, participants also identified a number of additional benefits of geothermal energy including energy security, just energy transition, and the potential for reuse of existing energy infrastructure (e.g., oil and gas wells) (Figure 17a).

The main applications identified by our stakeholder survey were use of geothermal for space heating, industrial heating and agriculture/ horticulture use (Figure 17b).

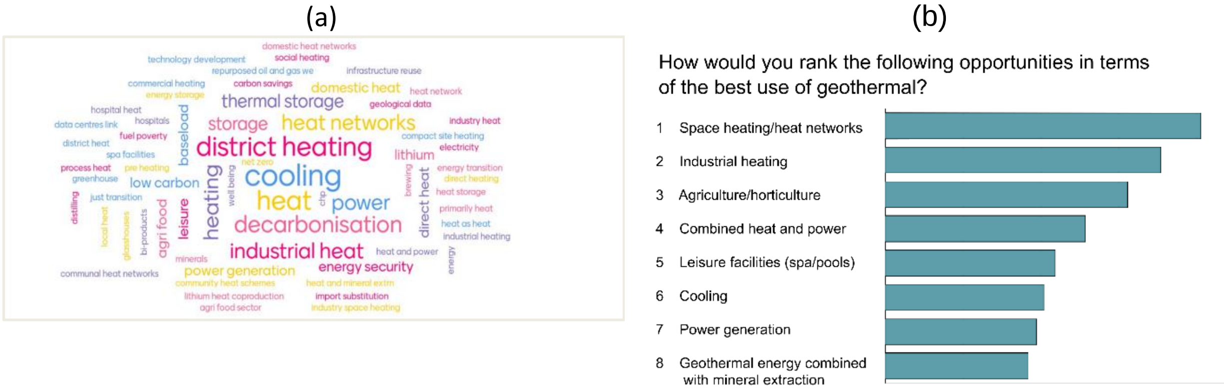

Figure 17: Main opportunities for deep geothermal in the UK identified (a) by workshop participants (word cloud) and (b) by online survey participants (bar chart).

There was consensus that geothermal opportunities are most likely to arise from the development of the resources for direct-use heating and thermal energy storage at depths between 1–3 km. This is because achievable temperatures in the UK's sedimentary basins (which make up most of the available potential, see Figure 11) are not expected to be sufficient for power generation within that depth range. Furthermore, geothermal heating technologies are seen to be more readily deployable than technology for power generation (i.e., they do not require construction of a power plant), and generally entail lower risks. This is mainly because they do not require very deep drilling (compared to power projects), and achieving a specific temperature is less critical, e.g., they can use heat pumps to achieve the required operational temperatures for the heat network. However, in a few areas of the UK, such as parts of Cornwall, favourable geological conditions could make geothermal power generation economically viable.

4.2 NET ZERO: DECARBONISATION BENEFITS

Geothermal energy is available across the UK at different depths and temperatures (Chapter 0). It can be exploited for geothermal heating applications, such as district heating, and is some places also for power generation.

Compared with other heating technologies, geothermal has one of the lowest carbon footprints (Table 4). [134] Hence deploying geothermal technologies could achieve considerable carbon savings. In Germany, deep geothermal technologies saved 158,000 tonnes of CO_2 equivalent from electricity generation and 500,000 tonnes of CO_2 equivalent from heating in 2021,[135] including geothermal heat networks. It is estimated that individual projects in the UK could deliver savings of between 2,400 tonnes[136] and 14,000[137] tonnes of CO_2 equivalent per year (compared with natural gas) for geothermal heating and power operations, respectively, achieving total savings in the range of 72,000 - 700,000 tonnes of CO_2 equivalent over the projects' thirty-year to fifty-year operational lifetime. For comparison, the UK Households

[134] Squires, J. & Goater, A. (2016). Carbon Footprint of Heat Generation. POSTnote 523.
[135] Bundesministerium für Wirtschaft und Energie (BMWi) (2021). Zeitreihen Erneuerbare Energien. Time series for the development of renewable energy sources in Germany, Status September 2022
[136] Hill of Banchory Consortium (2016). Hill of Banchory geothermal energy project: feasibility report. Scottish Government.
[137] Geothermal Energy Ltd. Manhay Deep Geothermal Project

heating emissions arising from the use of fossil fuels was 80 million tonnes CO_2 equivalent in 2019.[138]

Table 4: Carbon footprint estimates for non-electric space and water heating (from Squires & Goater, 2016).[134]

Technology	Footprint range (gCO_2eqkWh)	Number of estimates
Oil boilers	310-550	3
Gas boilers	210-380	6
Gas micro-Combined Heat and Power	220-300	4
Gas absorption heat pumps	150-200	4
Bio-sourced gasses	20-100	2
Biomass boilers	5-200 (most below 100)	9
Geothermal	10	1
Solar thermal	10-35	6

Technology	Electricity Footprint estimate	Footprint range (gCO_2eqkWh)	Number of estimates
Electric heaters	Current (370)	~370	Personal communication
	Reduced (250)	~250	
	Low (100)	~100	
Ground source heat pumps	Current (370)	70-190	15
	Reduced (250)	50-125	
	Low (100)	20-50	
Air source heat pumps	Current (370)	90-250	11
	Reduced (250)	60-170	
	Low (100)	30-70	

4.2.1 Heat networks

The UK's Climate Change Committee (CCC) predicts that around 20% of UK heat will need to come from heat networks[139] by 2050 if the UK is to meet its carbon targets cost-effectively. [140] Currently, approximately 12,000 communal heat networks and 2,000 district heating schemes are operational in the UK.[141] Until recently, heat network developments have focussed on using gas boilers (52%) and gas-fired combined heat and power (CHP, 32%).[142] From a carbon emissions perspective, support for this technology is declining and alternative heat sources need to be identified. Geothermal energy is identified in the Heat and Buildings Strategy as a potential supply for low-carbon heat networks.

Deep geothermal projects could provide a heat source for district heating in many parts of the UK. The size of the potential and the fact that geothermal energy is available 24 hours a day, 7 days a week makes it particularly suitable for base load provision with other heat sources such as biomass or waste heat covering peak loads. The city of Munich (Germany), for example, supplies around 50,000 homes with geothermal heating, saving about 75,400 tonnes of CO_2 per year compared with gas.[143]

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[138] DEFRA (2022) Official Statistics: Carbon footprint for the UK and England to 2019
[139] Miller, J. (2021). Heat networks.
[140] CCC (2020). The Sixth Carbon Budget: The UK's path to Net Zero. Committee on Climate Change
[141] BEIS (2018). Energy Trends: March 2018, special feature article - Experimental statistics on heat networks
[142] Miller, J. (2020). Heat Networks. POSTnote 632.
[143] Bendias, D. et al. (2019). From vision to reality: Unlocking the Geothermal Potential.

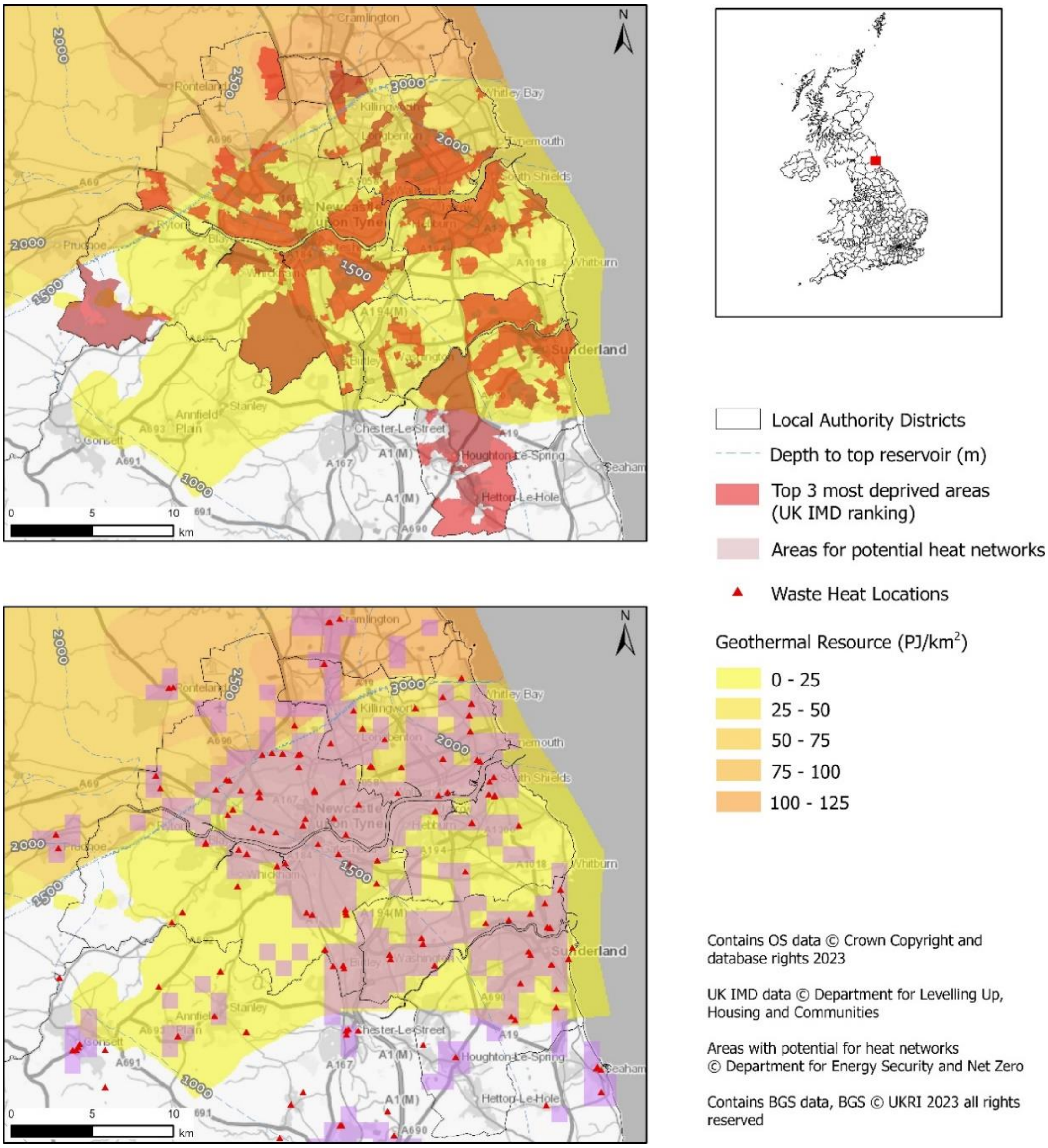

Figure 18: Map of North Tyneside, Newcastle, South Tyneside, Gateshead and Sunderland local authority districts. Top: shows the distribution of the Mesozoic Middle Border Group (Fell Sandstone) assessed geothermal potential (PJ/km^2)[144] in relation to the most deprived areas.[145] Bottom: shows the distribution of the Mesozoic Middle Border Group assessed geothermal potential (PJ/km^2)[144] in relation areas of potential heat networks[146] and industrial waste heat (from sewage treatment, supermarkets, iron/steelworks, food/drink, chemical and other mineral industries) locations[146] (© North East LEP).

In Stoke-on-Trent, the city council has given planning approval for a 14 MW "deep geothermal" energy project in the Etruria Valley. Two wells will be drilled to a maximum depth of 3,800 m to exploit potentially permeable fractures in the deep Carboniferous limestone aquifer of Northern England (Figure 15G). The anticipated water temperature is 95°C. 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[147] (sufficient to provide heating for around 4,000 homes). The

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144 Rollin, K. E. et al. (1995). Atlas of geothermal resources in Europe: UK revision. Technical report WK/95/07, British Geological Survey, Keyworth, UK

145 UK Index of Multiple Deprivation (IMD)

146 BEIS (2021). Building-level Heating and Cooling demand dataset based on Opportunity areas for district heating networks in the UK, 2021.

147 Stoke-on-Trent City Council et al., Stoke-on-Trent and Staffordshire City Deal

project has been delayed multiple times since its announcement in 2014.[148] The project was then impacted by the withdrawal of the Renewable Heat Incentive in 2021. Without the incentive, the proposed business case was no longer viable and alternative funding was needed for the project to progress. An energy purchase agreement is now in place with the energy company SSE, and drilling is expected to start once funding is finalised, possibly as soon as autumn 2023.

A national comprehensive assessment has identified opportunity areas for district heating in the UK,[149] including potential waste heat sources from sewage treatment, supermarkets, iron/steelworks, food/drink, chemical and other mineral industries. In many parts of the UK, these opportunity areas coincide with deep geothermal prospects as well as with areas of deprivation as shown in Figure 18 for the North Tyneside, Newcastle, South Tyneside, Gateshead and Sunderland local authority districts. Supporting geothermal developments in these areas could deliver a wide range of additional benefits, including fuel poverty alleviation and levelling up the UK. However, geothermal sources are currently not considered in the proposed Heat Network Zoning framework for England, hence there is a risk that this renewable resource will be overlooked.

4.2.2 Decarbonisation of the public sector estate

The public sector estate is a main emitter of greenhouse gases (for heating) after the domestic, commercial and industrial sectors. It emitted ~8,000 Kt CO_2 equivalent in 2020[150] from burning natural gas (Figure 19). The public sector estate includes many large buildings and complexes (such as hospitals, prisons, army barracks and office buildings) that have high, predictable heat demands and a continuous requirement for heating. Such buildings provide ideal anchor loads for geothermal projects as well as for district heating networks and are attractive to geothermal developers because of the potential for obtaining reliable, long-term heat purchase agreements.

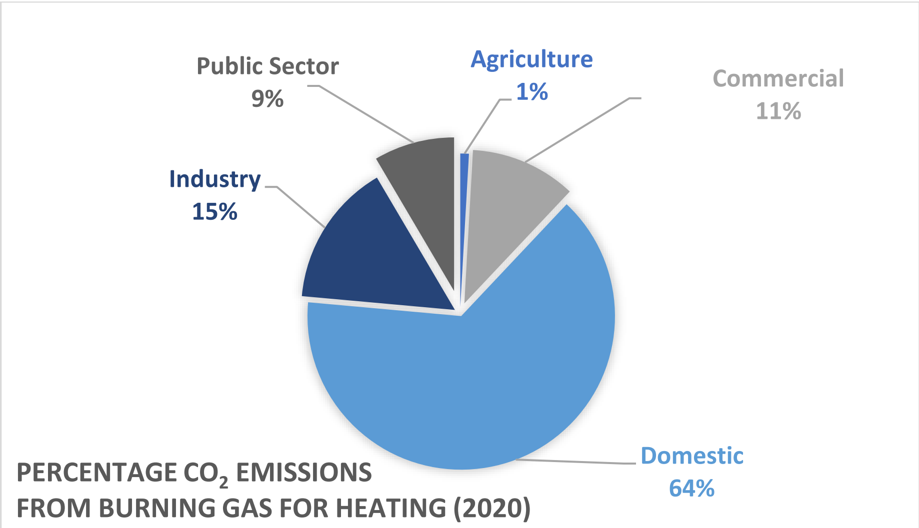

Figure 19: Sector emissions from burning of gas for heating (Source: GOV.UK[150] © Crown copyright 2022, available under the Open Government Licence v3.0).

The NHS hospital estate, for example, is made up of 1,228 hospitals and 217 NHS trusts.[151] It is responsible for around 4% of the nation's carbon emissions. In October 2020, the NHS became the world's first health service to commit to reaching net zero by 2040,[152] adopting a more

[148] Richter, A. (2014). UK Government funds million for geothermal heating project | ThinkGeoEnergy - Geothermal Energy News. ThinkGeoEnergy.
[149] BEIS (2021). Opportunity areas for district heating networks in the UK: Second National Comprehensive Assessment. UK GOV.
[150] BEIS (2022). UK local authority and regional greenhouse gas emissions. UK GOV
[151] Decarbonising the NHS hospital estate – Towards net zero
[152] NHS England (2020). Delivering a 'Net Zero' National Health Service

challenging Net Zero target for the NHS than the UK national target. The Carbon and Energy Fund (CEF) has identified the top 210 hospitals in England for decarbonisation based on their annual heat demand. An unpublished study by the British Geological Survey has shown that out the 210 sites identified by CEF, 109 sites overlie potential geothermal aquifers and three sites overlie radiothermal granites. The estimated drilling depths to reach a temperature of 50°C range between 1.2–3 km. Developing geothermal projects for these sites could save emissions between 1.3–22.7 kt CO_2 equivalent per year for individual hospital sites. Developing geothermal projects for the 30 top-ranking hospital sites (based on heat demand), as listed in Table 5, could save emissions of 281 kt CO_2 equivalent per year. For comparison, present day emissions from NHS England's hospital estate and facilities are around 2,300 kt CO_2 equivalent per year.[153]

Table 5: The 30 top-ranking (based on heat demand) hospital sites in England that overlie a deep geothermal prospect (BGS 2023, unpublished).

Site ranking (based on heat demand)	Annual heat demand (GWh)	Estimated Annual CO_2 Emissions (kt)	Estimated (average) drilling depth (m) to 50°C isotherm
1	88.3	22.7	1754
2	64.1	16.5	2127
3	63.7	16.4	1866
4	60.6	15.6	1764
5	51.1	13.1	2130
6	51.0	13.1	2406
7	45.9	11.8	1930
8	41.5	10.7	1869
9	40.9	10.5	2155
10	37.9	9.8	1847
11	37.7	9.7	1761
12	36.7	9.4	2484
13	33.7	8.7	2252
14	33.4	8.6	2318
15	32.9	8.5	2127
16	29.5	7.6	2500
17	29.5	7.6	2158
18	28.8	7.4	1772
19	28.3	7.3	2277
20	27.2	7.0	1974
21	26.4	6.8	2155
22	26.0	6.7	2142
23	23.9	6.2	1994
24	23.2	6.0	1784
25	22.3	5.7	1637
26	22.0	5.7	2120
27	21.8	5.6	1896
28	21.8	5.6	2128
29	21.4	5.5	1873
30	21.1	5.4	2128

153 NHS England (2022). Delivering a 'Net Zero' National Health Service

Retrofitting a geothermal heat source to existing buildings, such as hospitals, can be challenging. It may require an upgrade to existing or building of new heat networks. Where the geothermal resource has not been proven, the achievable heat loads will remain uncertain until the well has been drilled. This uncertainty may prevent uptake of geothermal heating by the public sector.

4.2.3 Delivering benefits to multiple users

Geothermal projects can deliver benefits to a range of end users with different heating requirements (i.e., consecutive use of the produced steam/water for more than one application, typically with decreasing temperature requirements) (Figure 20). This, so called, "cascaded use" of heat and/or power increases net efficiency of a geothermal plant and improves the economic feasibility of the project. International examples from countries such as the United States, Austria and Iceland show that cascaded use can reduce net payback times by 50–70%.[154]

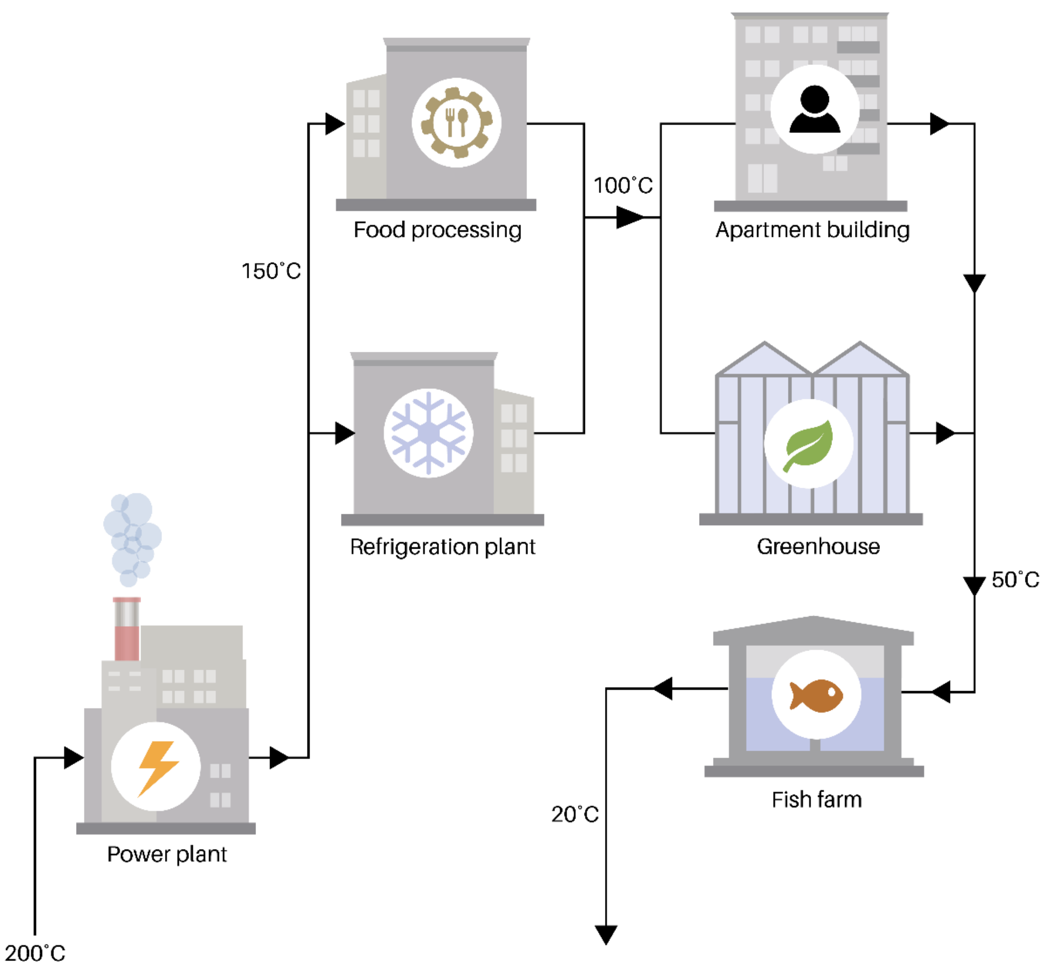

Figure 20: Cascaded use of geothermal heat and power. Adapted from Brophy et al. (2015)[154] (BGS @ UKRI 2023).

4.3 ECONOMIC BENEFITS: GREEN GROWTH AND NORTH SEA TRANSITION

As well as emissions savings, geothermal projects can provide economic stimulus and contribute to job generation. Geothermal Engineering Limited (GEL) estimated that the United Downs project has contributed £1.5 million to local economy across a range of sectors, including food & hospitality; groundworks engineering, security services; health & safety supplies and monitoring services (Figure 21).[155]

[154] Brophy, P. et al. (2015). Cascaded Uses of Geothermal Energy. Presentation.
[155] Geothermal Engineering Ltd. Future Sites.

In Germany, the geothermal industry (all technologies) has generated €16.7 billion since 2000[135] and created 35,900 jobs.[156] Depending on the size of the project, each geothermal heating and electricity project create up to 30 and 100 direct jobs, respectively, in areas such as exploration, construction, operation & maintenance, planning, and research (Figure 17).[157] An estimate from the Eden Geothermal project suggest that actual employment numbers may actually be higher during some project phases (see Table 6). Many of the personnel in the project may have come from the oil and gas sector, hence geothermal also offers an opportunity for transitioning existing technologies, expertise, and skills.

Table 6: Estimated numbers of Full Time Equivalent (FTE) jobs at the Eden Geothermal Project during different phases of project development.

Core staff	Site preparation	Drilling (1 well)	Testing & monitoring	Heat main / MEP installation	Heat operation
Permanent	4 months	6 months	variable	8 months	permanent
7 FTE core staff	+ 4 FTE	+ 6 FTE		+ 6FTE	+ 1 FTE
	~15 contractors	Drill crew & contractors: 24-hrs operation alternating crews with 35-40 staff each = ~150 FTE	~ 12 contractors including 24-hrs seismic monitoring	~ 25 contractors	
Number of jobs (FTE)	**26**	**164**	**19**	**37**	**8**

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.[158]

There are currently 32 deep geothermal projects in development or under consideration in the UK (Figure 11; Appendix 1). Some of the proposed projects have been paused but could be revived given the right incentives.[159] If progressed, these projects could create over 1,000 direct jobs and 2,500 indirect jobs in the short-term as well as bringing economic stimulus to the respective local areas. In the long-term, it is estimated that building the sector to reach 360 projects by 2050 could create over 10,000 direct jobs and a further 25,000 indirect jobs.

The UK has extensive expertise in exploration and drilling for oil and gas, both onshore and offshore in the North Sea, East Irish Sea, West of Shetland etc. Requiring similar skillsets and supply chains as oil and gas exploration, geothermal projects could offer direct employment opportunities for employees transitioning from the oil and gas sector. These might include well site geologists, drillers, mud engineers, wireline loggers, water engineers, rig crew and casing engineers. There are also opportunities for directly re-purposing O&G wells (Section 4.6.1). 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. For example, industry reported that the 11 responses received to their drilling tender included only two UK companies. However, their rigs were not able to drill to the required specifications and hence the project had to source the drilling rig and crews from outside the UK, adding extra costs and potential interruptions to projects.

[156] Bundesministerium für Wirtschaft und Energie (BMWi) (2023). Bruttobeschäftigung durch erneuerbare Energien 2000 bis 2021.
[157] Arup (2021). Deep Geothermal Energy. Economic Decarbonisation Opportunities for the United Kingdom.
[158] Dutch Association Geothermal Operators, Stichting Platform Geothermie, Stichting Warmtenetwerk and EBN (2018). Master Plan Geothermal Energy in the Netherlands.
[159] Townsend, D. et al. (2020). "On The Rocks" – Exploring Business Models for Geothermal Heat in the Land of Scotch, Proceedings World Geothermal Congress 2020, Reykjavik, Iceland, April 26 – May 2, 2020.

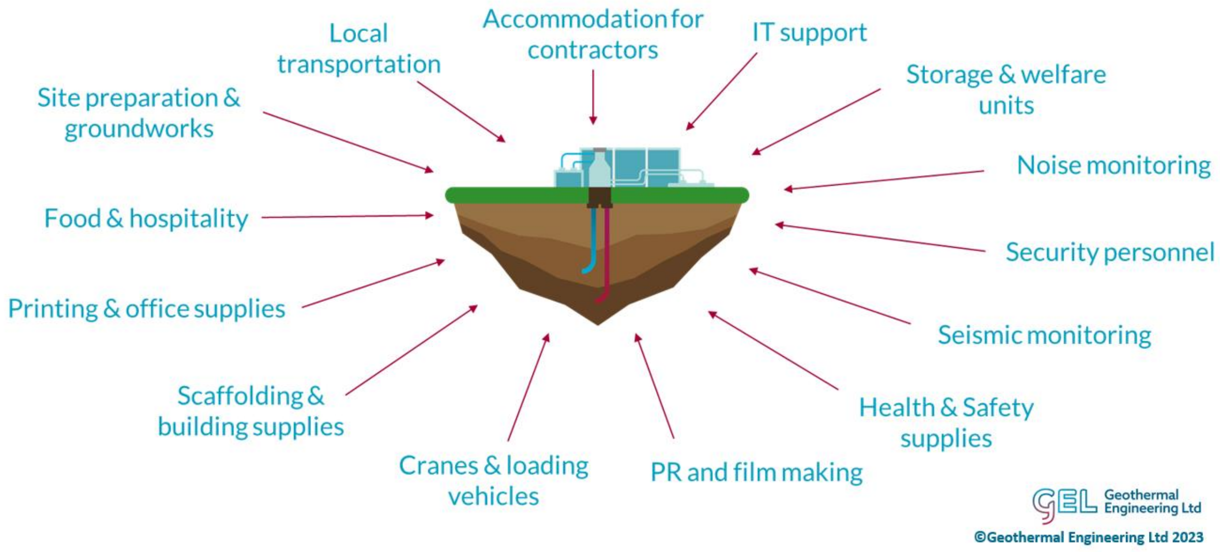

Figure 21: Sectors that have benefited from the development of United Downs Project in Cornwall, which contributed £1.5 million to the local economy (reproduced with permission from GEL).[160]

Developing a UK deep geothermal industry and supply chain could provide a unique opportunity for the UK's oil and gas sector to transition their jobs and economic activity to a low-carbon technology, thereby supporting the government's North Sea transition agenda. This is an area that is currently being developed by a number of groups in the UK, including the Net Zero Technology Centre, Shift Geothermal and the Geothermal Energy Advancement Association.

In addition, various studies have identified potential for extracting deep geothermal heat from existing oil and gas fields, onshore[161, 162] and offshore [163] (see Section 4.6.1).

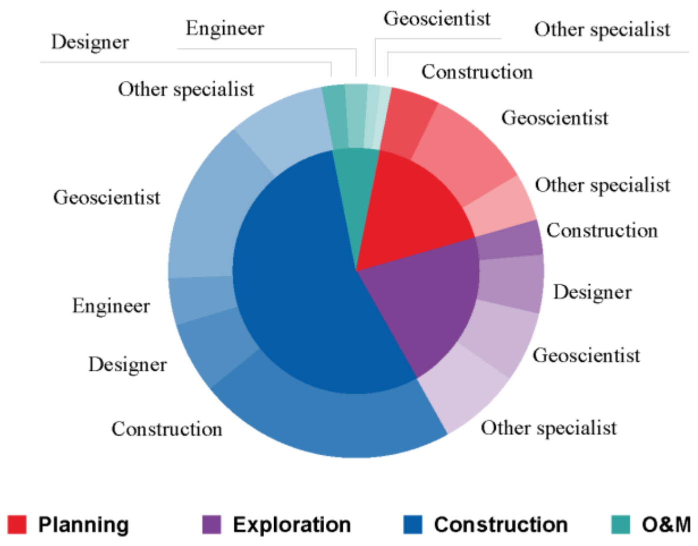

Figure 22:Direct jobs for a typical geothermal project (© ARUP).

[160] Geothermal Energy Ltd. Future Sites.
[161] Watson, S. M. et al. (2020). Repurposing Hydrocarbon Wells for Geothermal Use in the UK: The Onshore Fields with the Greatest Potential, Energies, vol. 13, 3541.
[162] Hirst, C. M. & Gluyas, J. G. (2015). The Geothermal Potential Held within Carboniferous Sediments of the East Midlands: A
New Estimation Based on Oilfield Data Proceedings World Geothermal Congress 2015 Melbourne, Australia, 19-25 April 2015.
[163] Jones, D. (2020). Offshore data availability for Carboniferous Limestone in the assessment for deep geothermal energy in the UK Southern North Sea, Q47-48.; BGS Internal report IR/20/002.

4.4 SOCIAL BENEFITS: LEVELLING UP

Many of the UK's deep geothermal opportunities are in areas that are identified by the UK Community Renewal Fund [164] as the top 100 places in the UK in need of economic stimulus, including North East England (e.g., Figure 18) and Cornwall. These areas are identified based on several indicators including productivity, skills, unemployment rate, population density and household income. A comparison between Figure 16 and Figure 23 shows where UK prospects coincide with areas of below UK average income and productivity (grey areas and lighter shades). Investment in deep geothermal in these areas could contribute to addressing energy poverty and to the levelling up agenda which remains a key government priority.

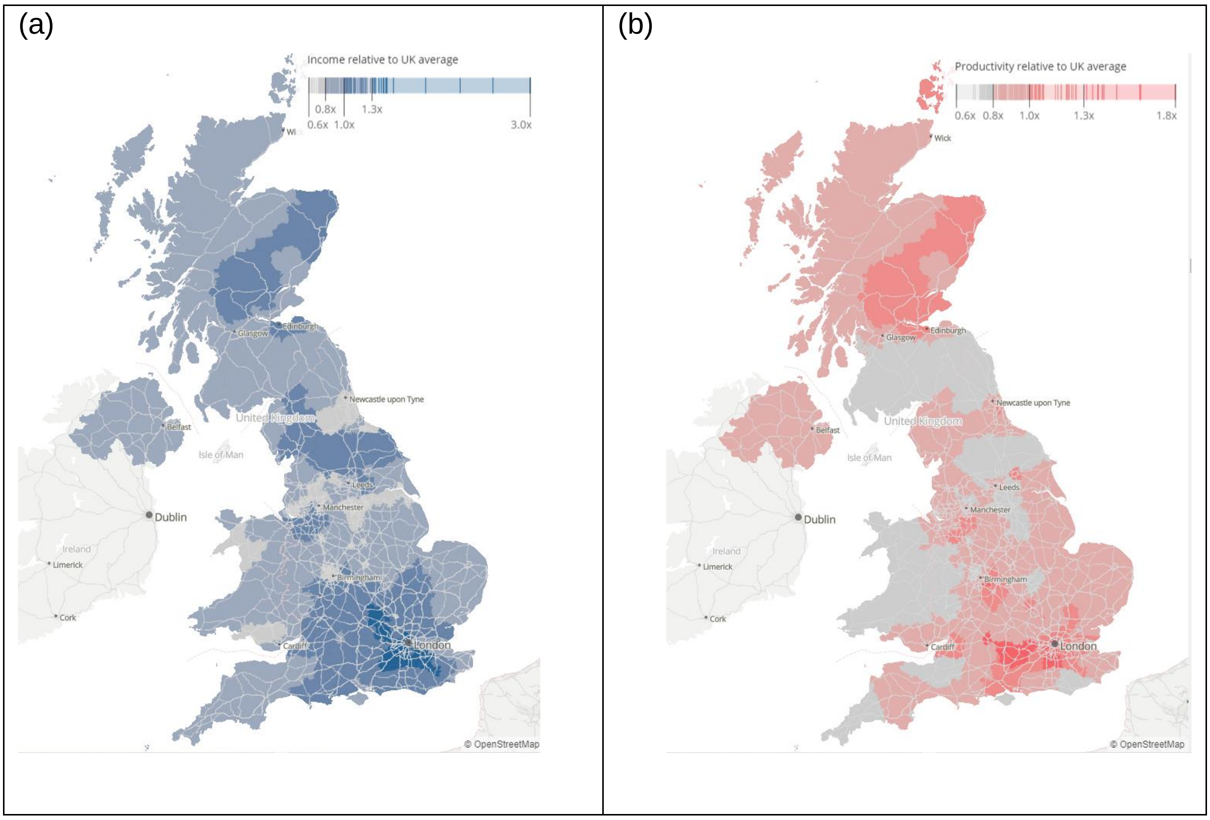

Figure 23: Economic indicators for 2018 for the UK: household income (a) and productivity (b) (both shown in relation to UK average). Source: Office for National Statistics 2021[165] © Crown copyright 2021, available under the Open Government Licence v3.0. © OpenStreetMap contributors.

4.4.1 Tourism and wellbeing

Many countries have spas and resorts that have swimming pools heated with geothermal water (including balneology – the treatment of diseases with water).[166] The thermal spas and resort industry enjoys significant economic benefits from using geothermal energy. In addition to emission savings, geothermal energy has been reported to provide considerable social benefit for tens of thousands of people each year, including improved quality of life through availability of affordable recreational facilities for swimming, bathing and therapy, as well as providing some local income through tourism.

In the Eastern US, where geothermal energy is derived from radiogenic granites and deep sedimentary basins, like in the UK, use of geothermal water has enabled numerous swimming

[164] UK Government (2021). UK Community Renewal Fund: prioritisation of places methodology note.
[165] ONS (2021). What are the regional differences in income and productivity?
[166] Lund, J. W. & Boyd, T. L. (2016). Direct utilization of geothermal energy 2015 worldwide review, Geothermics, vol. 60, pp. 66–93.

pools and spas to remain in business despite of high fuel costs while also saving emissions of at least 7,333 tonnes of carbon dioxide each year – the equivalent of 17,300 barrels of oil. [167]

Geothermal spas and water parks have also been associated with an increase in local tourism and local economic growth in Poland where many geothermal bathing centres or spas emerged because of the development of geothermal heating networks.[168] In the UK, the Thermae Spa facilities at Bath (Figure 11) attract an average of 260,000 visitors a year, contributing £14.6 million to the local economy.[169] The Rogner Bad Blumau Hotel and Spa (Austria), which is heated using waste heat from a geothermal power plant (cascading use), is said to attract 40,000 tourists each year annually, providing 340 jobs.[154] In Germany, thermal spas are estimated to generate €26 billion annually and employ over 350,000 people. [170]

In the UK, the geothermally-heated Jubilee pool in Penzance offers Locals' Discount of 20% for people living in Penzance as well as tailored therapies and programmes for up to 180 people per week aimed at improving the health and well-being of people with ill health, disability, social isolation/exclusion, or affected by substance abuse/addiction issues.[171]

4.5 ENERGY SECURITY

Geothermal energy is available in many parts of the UK, 24 hours per day and independently of the weather. A well-developed geothermal sector could produce geothermal heating (and some electricity) with little reliance on external factors like skills and supply chains. It does not require critical minerals for construction of its infrastructure. This security of supply of geothermal energy makes it an attractive energy source that could significantly reduce our reliance on third country suppliers of gas, thereby contributing to increase Energy Security in the UK. Furthermore, geothermal energy provides a decentralised energy source that is available over wide geographical range (see Figure 11).

4.6 LINKS TO OTHER TECHNOLOGIES AND SHARED BENEFITS

4.6.1 Repurposing of existing wells

There are many onshore boreholes (about 2100) across the UK that have been drilled for oil, gas, unconventional hydrocarbons, coal bed methane or other purposes. Some are exploration boreholes, whilst others were developed for production. A small number of these boreholes may be suitable for re-use for geothermal purposes[172,173] (Figure 11), provided they have not yet been fully decommissioned and there is a nearby consumer (e.g., horticulture or agriculture use). Re-using abandoned hydrocarbon wells to produce geothermal heat and electricity could reduce costs of geothermal projects. There have also been studies that have looked at the repurposing of wells offshore to deliver geothermal hot water and/or electricity to oil and gas platforms.[174,175]

Some examples of repurposing include: CeraPhi Energy[176] has developed a new proprietary closed-loop technology for extracting energy from deep wells. Initial designs for the CeraPhiTru™ unit were successfully completed by Petrofac in 2022 and a manufacturer has been appointed by CeraPhi Energy with development of the first units expected to start imminently. The Helix borehole in Newcastle (1.6 km depth) was drilled in 2011 but did not

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[167] Chiasson, A. (2011). The Economic, Environmental, and Social Benefits of Geothermal Use in the Eastern United States, Geo-Heat Center, Oregon Institute of Technology.
[168] Kurek, K. A. et al. (2020). Geothermal spas as a local development factor, the case of Poland, Geothermics, vol. 85, 101777.
[169] Andrews, H. (2014). Thermae Bath Spa becomes major tourism beacon for famous UK city. Attractions Management.
[170] Bakopoulou, R. & Papatheodorou, A. (2011). Funding Thermal Tourism in Greece and Germany: A Comparative Case Study; 3rd Conference of the International Association for Tourism Economics; Bournemouth, UK.
[171] Jubilee Pool (2018). Jubilee Pool Penzance: Project Business Plan
[172] Watson, S. M. et al. (2020). Repurposing hydrocarbon wells for geothermal use in the UK: The onshore fields with the greatest potential. Energies, vol. 13, 3541.
[173] Environment Agency (2022). Specific environmental risks from repurposing oil and gas wells
[174] Gluyas, J. G. et al. (2018). Geothermal Potential of the Global Oil Industry
[175] Cariaga (2023) Consortium completes first-of-its-kind offshore geothermal assessment project. Thinkgeoenergy
[176] https://ceraphi.com/

provide the expected flow rates. It is now being redeveloped as part of the NetZero GeoRDIE project[177] with funding from UK Research and Innovation. In addition, investigations are underway in the District of Ryedale (North Yorkshire) to establish if existing shale gas wells can be repurposed to provide geothermal heating to homes and businesses.[178]

Apart from economic and technical challenges, several regulative changes and legal challenges need to be addressed, including the relationship with the decommissioning regime and liability issues. Under current licensing arrangements for which NSTA is the regulator, it is not possible to transfer from an oil and gas licences to geothermal use. Clearer assignment of responsibilities (authority responsibility for geothermal energy) and introduction of geothermal licensing regime may be needed to address this.

4.6.2 Geothermal and CCS

There is increased interest in combining geothermal energy production and Carbon Capture and Storage concepts. Such concepts include the use of supercritical CO_2 as heat transfer medium for geothermal energy production which has potential to increase the overall efficiency of heat extraction due to the more favourable hydrodynamic properties of CO_2 compared with water. Other concepts propose dissolving CO_2 (e.g., from industrial sources or captured from geothermal steam) in the geothermal brine and co-injecting it into the geothermal reservoir for storage of CO_2 as part of the geothermal operations. These concepts are at various stages of development ranging from being largely conceptual (i.e., supercritical CO_2 as working fluid) to operational pilot plants (carbon fixture in geothermal reservoirs). A detailed review of these concepts and linked synergies (i.e., concurrent use of reservoirs for geothermal and CCS operations) has been completed recently for the International Energy Agency Greenhouse Gas R&D Programme (IEAGHG).[179] The review highlighted the different stages of maturity of the proposed technologies, including future research and innovation needs.

4.6.3 Geothermal and Underground Thermal Energy Storage

There is also increased interest in combining geothermal energy production and Underground Thermal Energy Storage (UTES). UTES technologies are very versatile, including thermal energy storage in aquifers, boreholes, and abandoned mines. Combining UTES with geothermal energy production offers opportunities for storage of excess heat during time of low demand or to provide a backup heat source during periods of well maintenance. Research on UTES is progressing in the UK (e.g., the UK-funded ATESHAC project[180]) and internationally, including the combined application of geothermal production and thermal energy storage (e.g., the EU-funded PUSH-IT project[181]).

4.6.4 Co-production

Geothermal fluids can contain valuable metals such as lithium: an important raw material in battery production.[182] Lithium is found in the geothermal waters in Cornwall and Weardale. [183,184] Pilot projects in Cornwall [185] and worldwide are testing different methods for the extraction of lithium from geothermal brines. If proven economical, co-production of lithium and geothermal energy could provide an additional value stream for geothermal energy. In the medium to long term, other elements such as rare earth elements may also be produced from geothermal brine. Other existing uses of material extraction include the sale of silica to the cement industry, CO_2 to the food and beverages industry, or some other minerals for cosmetics.[186] According to Blake

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[177] The Net Zero GeoRDIE project
[178] Gazette&Herald (2022). Ryedale gas wells could heat homes and businesses
[179] IEAGHG (in press) "Prospective integration of Geothermal Energy with Carbon Capture and Storage (CCS)" Report commissioned by the IEA Greenhouse Gas R&D Programme, 2023-02, awaiting publication.
[180] https://www.imperial.ac.uk/earth-science/research/research-groups/ateshac/
[181] https://www.push-it-thermalstorage.eu/
[182] British Geological Survey (2020). Raw materials for decarbonisation: The potential for lithium in the UK
[183] Manning, D. a. C. et al. (2007). A deep geothermal exploration well at Eastgate, Weardale, UK: a novel exploration concept for low-enthalpy resources. Journal of the Geological Society, vol. 164, pp. 371–382.
[184] Early, C. (2020). The new 'gold rush' for green lithium.
[185] Cornish Lithium Ltd. GeoCubed..
[186] EGEC (2020). EGEC policy paper.

et al. (2020)[187], examples exist in the USA where zinc is extracted in economically viable amounts from geothermal fluids. As such, geothermal has potential to contribute to the UK's security of supply, although the capacity is likely to be small.

4.7 FUTURE TECHNOLOGIES

4.7.1 Unconventional technologies

Development of unconventional technologies has potential to unlock geothermal potential in areas that currently cannot be exploited cost effectively. For example, Busby and Terrington (2017)[188] calculated a total technical potential for geothermal power generation in the UK of 222,393 MW_e. This estimate considers all heat stored in the ground to a depth of 6.5 km, irrespective of geology. With current technologies, only a fraction of less than 1% of this value can be economically exploited. However, technology development, in particular improvements in drilling technologies, and reduction in costs, are expected to make more of the deep, hot subsurface accessible for exploitation, and as a result deep geothermal opportunities are likely to grow to include all parts of the UK. The minimum drilling depth needed to reach 50°C and 150°C (the current threshold for direct use heat and power generation, respectively) across the UK is shown in Figure 24. Lighter colours represent shallower drilling depth. Unlocking part of this currently inaccessible heat might be achieved by some of the innovative technologies described below.

4.7.2 Advanced geothermal systems (AGS)

Advanced Geothermal Systems are a very deep, purpose-drilled closed loop systems that transfer heat via conduction from the ground to a working fluid. Different designs exist, with the most advanced design at present being the Eavor-Loop™.[189] It consists of continuous loops drilled into the ground to depths of several kilometres, using advanced drilling techniques. The boreholes are sealed from the adjacent rock using proprietary techniques to create loops within which the working fluid can be circulated. Lateral boring, with many horizontal or sub-horizontal multilateral offshoots can be drilled to increase the contact area with the ground, creating a radiator-like pattern. The working fluid is circulated using a thermosiphon effect, whereby colder, denser fluid flows downwards and warmer lighter fluid flows upwards, reducing pumping costs. A heat exchanger or turbine at the surface is used to transfer heat for direct use heating or power generation.

Completing the first prototype geothermal plant in a sandstone reservoir in Canada in 2019 (producing ~11,250 MWh of thermal energy during its first two years of operation)[190], 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. The company launched its first commercial site in 2022, currently developing further sites in the US (Granite reservoir) and Germany (Carbonate reservoir). Like the Deep Geothermal Single Wells, the technology has potential to make geothermal heat and power accessible (almost) everywhere irrespective of geology (Figure 24).

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[187] Blake, S. et al. (2020). An assessment of geothermal energy for district heating in Ireland. Geological Survey Ireland.

[188] Busby, J. & Terrington, R. (2017). Assessment of the resource base for engineered geothermal systems in Great Britain, Geothermal Energy, vol. 5.

[189] https://www.eavor.com/

[190] https://natural-resources.canada.ca/science-and-data/funding-partnerships/funding-opportunities/current-investments/eavor-loop-demonstration-project/21896

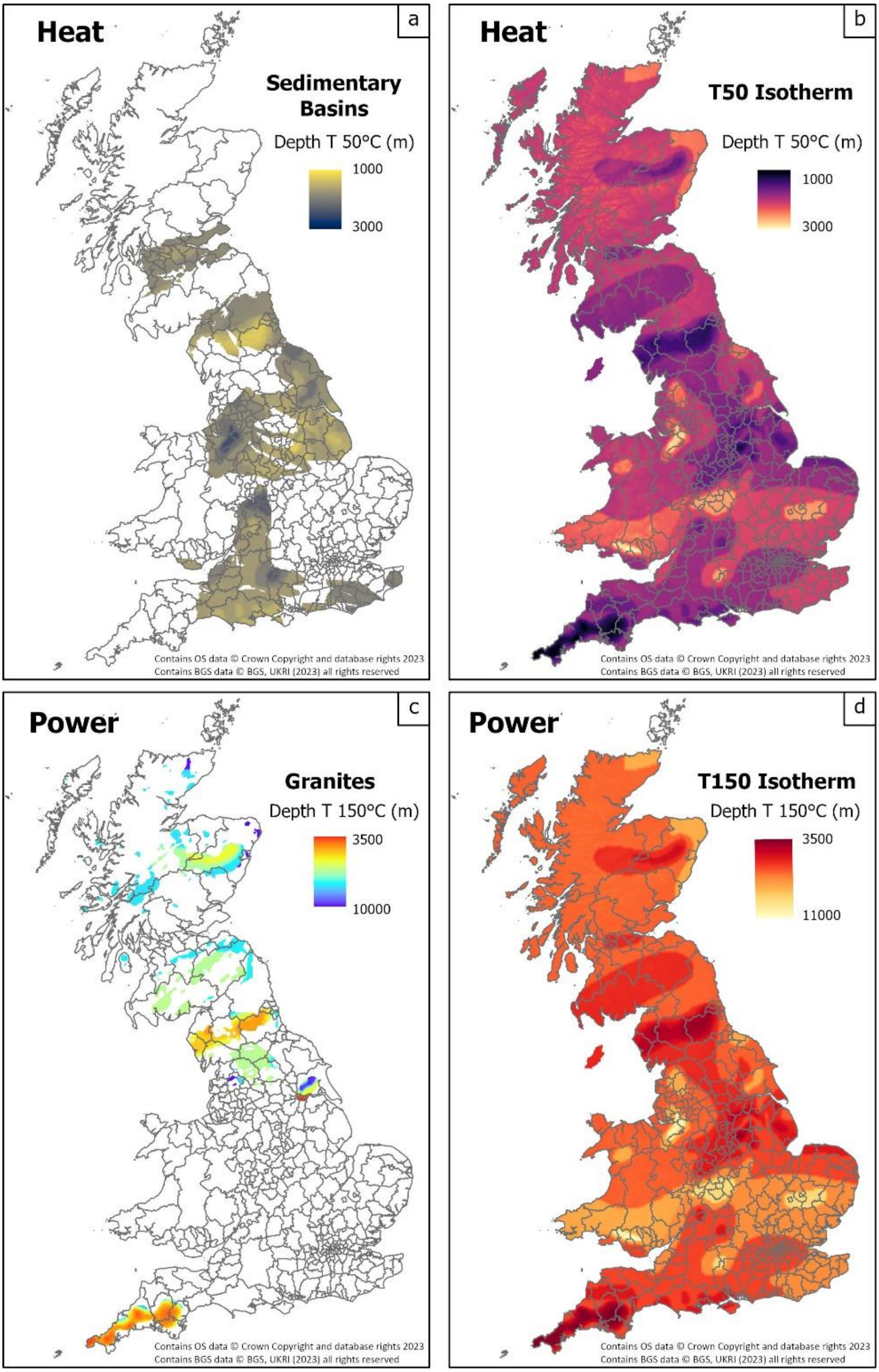

Figure 24: Top: Depth to 50°C isotherm with potential for geothermal direct use in (a) sedimentary basins (hot sedimentary/fractured aquifers) and (b) across all Great Britain via alternative technologies (closed-loop, coaxial wells, etc.). Bottom: Depth to 150°C isotherm with potential for power production in (c) granites and (d) across all Great Britain via alternative technologies. Isotherms were calculated using the equations, thermal properties, and heat flow data from Busby & Terrington (2017).[188] Data for Northern Ireland are not available. Note that depth scales are different for the T50 isotherms (a+b) (i.e. 1,000 to 3,000 m) and the T150 isotherms (c+d) (i.e. 3,500 to 11,000 m) (BGS © UKRI 2023).

4.7.3 Superhot rock systems (SHR)

Ultra-deep geothermal technology called Superhot Rock Systems (SHR) are a deeper variety of Enhanced Geothermal Systems. The depth of a SHR system is site specific. Ideally, a target depth would be 7 to 15 km below ground within high crystalline rock, however, due to drilling limitations, only shallow SHR systems have been completed to date up to depths of 3 to 7 km below ground. SHR may provide an opportunity in the future, but the technology is in its infancy and further technological advances and innovations are needed before these systems become viable, including new drilling technologies. Projects like the Krafla Magma Testbed in Iceland, or the planned targeted project at Newberry in Oregon, U.S. will be crucial in this regard.

4.7.4 Drilling innovation and new technologies

The CAPEX for deep geothermal is heavily linked to drilling costs, and so even small improvements in drilling technology could deliver considerable benefits to geothermal projects. Current drilling technology can reach depths of 7 km. Figure 24 shows that at this depth many areas of the UK reach temperatures of > 150°C. Drilling to those depths is not economically feasible at present because of the high time and cost requirements.

Current developments in drilling technology focus on drilling deeper, to hotter environments, and faster. Quaise Energy,[191] for example, is developing ultra-deep (up to 20 km) drilling technology that uses millimetre wave drilling to vaporize and vitrify the deeper basement rock. It will increase drilling velocity by reducing the need for complex downhole equipment (i.e. reducing non-productive rig time needed for pulling pipes and/or replacing drill bits) and enable drilling to greater depth. Currently at the laboratory testing stage, Quaise Energy anticipates deployment of the technology in 2–3 years with a first well to be drilled in 2026.[192] They predict drilling costs of $1000 per metre when the technology is established, enabling levelised costs of electricity (LCOE) of $40 per MWh.

Other new deep drilling technologies may become available in the shorter term. The EU-funded project ThermoDrill, for example, developed and tested a new drilling technique based on the combination of conventional rotary drilling with water jetting. First results suggest that this technology could double the drilling speed and reduce drilling costs for a deep borehole (5 km) by approximately 20%.[193] Another EU-funded project, Geo-Drill, developed a down-the-hole hammer that aims to reduce drilling costs by 60%.[194]

4.7.5 Heating technologies

High Temperature Heat Pumps (HTHPs) have a deployable temperature of up to 100°C[195] or even more (Very High Temperature Heat Pumps) that would increase the capacity of geothermal plants for both heat and power. The use of HTHPs at large scale would allow the utilisation of geothermal reservoirs with temperatures below the supply temperatures required for district heating networks.

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[191] https://www.quaise.energy/

[192] Houde, M. (2023). Unlocking the True Power of Clean Geothermal Energy, Northern Ireland Geothermal Webinar Series, 12 January 2023.

[193] EU-CORDIS (2020). CORDIS Results Pack on geothermal energy, 2020.

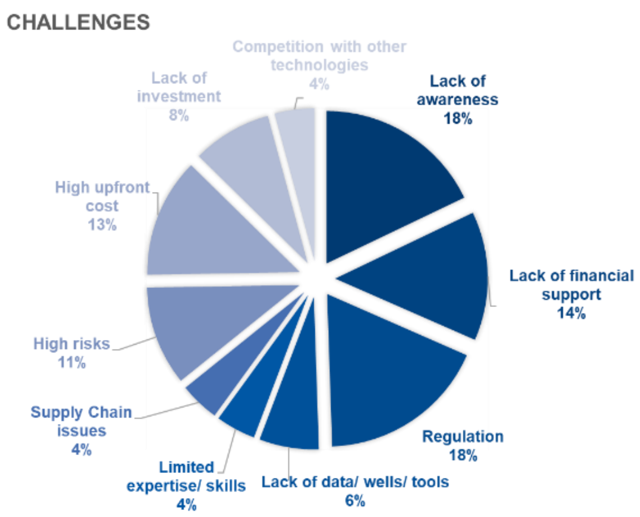
[194] EU-CORDIS (2022). CORDIS Results Pack on geothermal energy, 2022.

[195] Arpagus, C. et al. (2018). High temperature heat pumps: Market overview, state of the art, research status, refrigerants, and application potentials. Energy, vol. 152, pp. 985–1010.

5 UK stakeholder views of challenges and constraints

The stakeholder engagement which was undertaken as part of the white paper development has been described in Section 1.4. This section gives an overview of the challenges for geothermal energy in the UK which were identified by stakeholders during this engagement and in related studies, including the EAC inquiry [196] summarised in Arnhardt et al. (2023)[197] and studies by Abesser et al. (2023)[198] and Hambley et al. (2023).[199]

(a)



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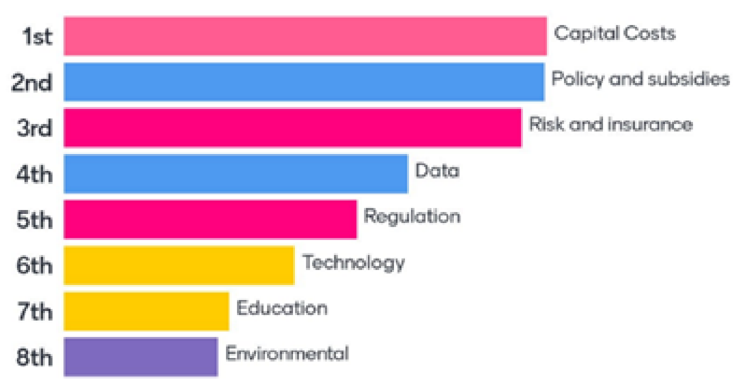

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[196] Environmental Audit Committee (2022). Inquiry into Technological Innovations and Climate Change: Geothermal Technologies.
[197] Arnhardt et al. (2023). Geothermal Technologies - Analysis of written evidence from the Environmental Audit Committee inquiry, BGS Internal Report, IR/23/001.
[198] Abesser, C. et al. (2023). Visualising geothermal regulations for the UK. Research brief. Unconventional Hydrocarbons in the UK Energy System (UKUH) project. Newcastle University.
[199] Hambley et al. (2023) Regulation and public decision making in geothermal energy – Workshop report, NERC Unconventional Hydrocarbons in the UK Energy System (UKUH) project.

(C)

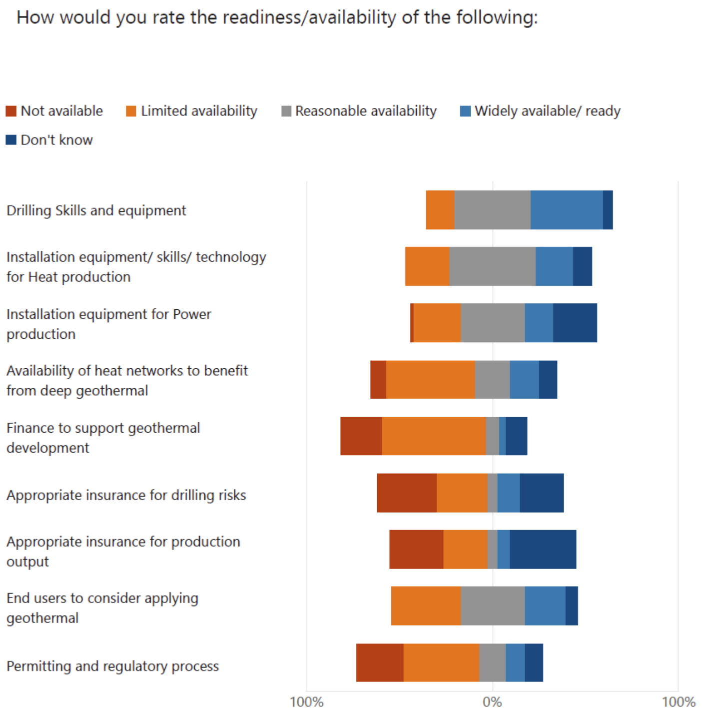

Figure 25: (a) Challenges highlighted by written evidence submitted to the EAC inquiry[197] (from Arnhardt et al 2023) and (b) by workshop participants (ranked by priority from high to low) (© North East LEP). (c) Readiness/ availability rating for different parts of the UK geothermal sector, including skills, funding, regulations, and demand or supply chains (online survey) (© North East LEP).

From the different strands of evidence, a combination of factors are identified which are perceived to constrain the development of a deep geothermal sector in the UK (Figure 25). The main challenges identified by the stakeholders can be grouped into the following categories:

1. Project costs and risks
2. Technology awareness
3. Government support and investment
4. Data availability
5. Supply chain and skills
6. Technology readiness
7. Regulation

The following section will further investigate these challenges, drawing on the feedback and discussion from the workshop, interviews and related studies and stakeholder events.

5.1 PROJECT COSTS AND RISKS

(1) *Stakeholders highlighted that uptake of the technology is inhibited by the high capital costs and that projects currently need support to improve their commercial viability.*

Current deep geothermal developments in Cornwall, for example, have only been able to proceed through support from the European Union, provided by the European Regional Development Fund. Since the UK's departure from the EU, this funding is no longer accessible by UK-based projects.

The capital expenditure (CAPEX) for deep geothermal heat project makes up 84% of the overall fixed project costs, most of which is spent on drilling and materials (Figure 5). CAPEX, therefore, varies based on the number and depth of boreholes, typically ranging between £2 million to £4 million per MW_{th} of heat capacity.[200] See also section 5.3.

(2) *Stakeholders highlighted that exploration and drilling risk are seen as a major barrier to wider uptake of geothermal technology in the UK.*

The geological and financial uncertainty over the subsurface conditions and volume of revenue that will be delivered, together with its timeframe, create risks for project developers and investors. Stakeholders have highlighted that these risks are considered a main barrier to wider uptake of geothermal energy in the UK as they make it difficult to obtain project finance or justify the spend, especially if lower risk options are available.

The risk profile for a typical deep geothermal project is presented in Figure 26. Risk of project failure is higher at the start of the project because there is limited information on the deep geology. The risk reduces after the drilling of the first well as it decreases the uncertainty regarding the temperature and flow rate, which define the capacity of the geothermal project, and therefore the revenue, which requires a large investment expenditure.

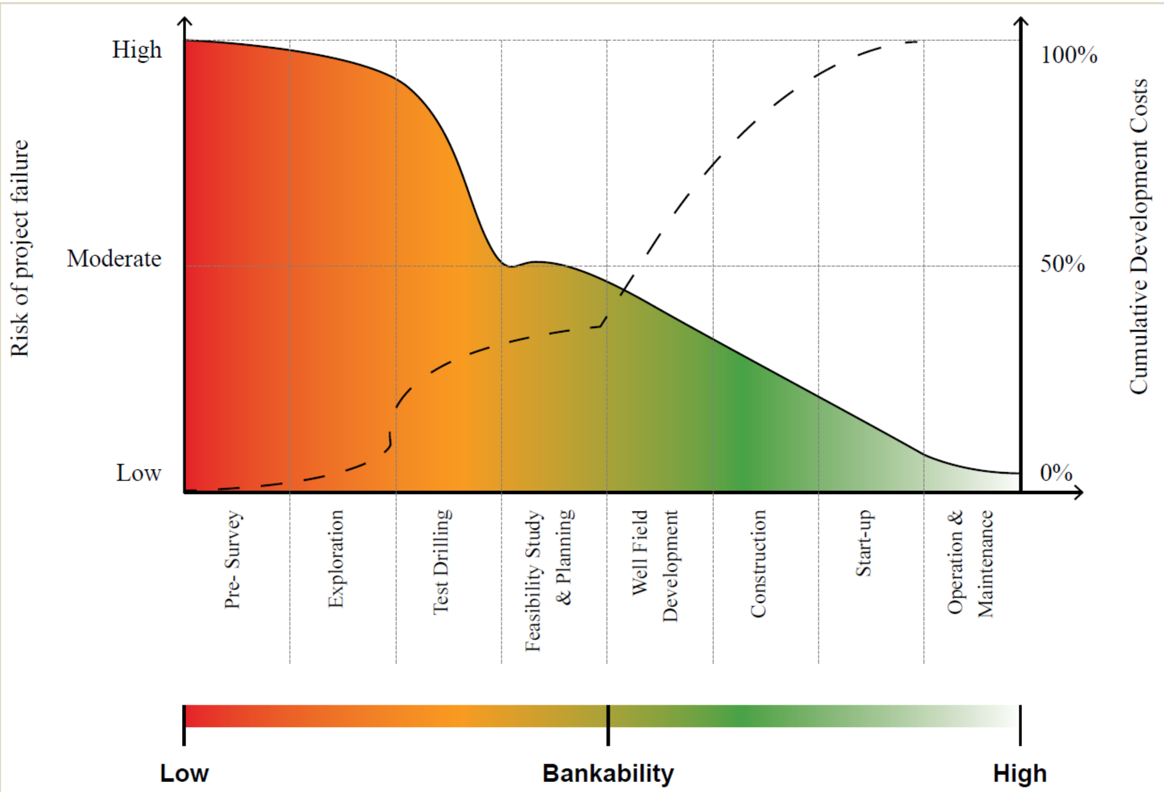

Figure 26: Deep geothermal risk profile (©Arup).

Geothermal risk mitigation schemes are highlighted by the European Geothermal Energy Council as one of the key mechanisms to stimulate the development of deep geothermal projects, especially during stages of low market maturity. Such schemes currently do not exist in the UK.

[200] Arup (2021). Deep Geothermal Energy – Economic Decarbonisation Opportunities for the United Kingdom

Stakeholders have identified a need for risk-sharing mechanisms for geothermal projects, e.g., through risk-insurance/ warranty schemes.[197,201] Some suggested risk sharing through provision of a rolling fund or loan, for example to support the decarbonisation of public sector estates, including high heat users such as hospitals. A grant of £100 million (or a loan available for five years), for example, was seen as sufficient to initiate a pipeline of deep geothermal projects. The loan/fund would be used to support the development of five deep geothermal projects. After two years it will fund a further five new projects, becoming self-sufficient after five years by using the revenue from the operational schemes to sustain further deep geothermal developments.

Risk sharing measures are especially important during early stages of market development and for technologies that are perceived by investors as high risk.

5.2 TECHNOLOGY AWARENESS

(3) *Stakeholders identified that technology recognition and awareness are seen as low amongst some groups and that geothermal energy is not represented in Government policy documents and renewable targets.*

The survey identified that awareness of geothermal energy technologies is seen to vary amongst different public groups, and some stakeholders reported that policy makers and potential end-user and/or clients are not aware of geothermal technology as an option (Figure 27). They perceive a lack of recognition of geothermal technologies amongst policy makers (central government and regulators) and potential end users (local councils, site and building developers).

In a different study,[202] stakeholders stated that "there is no culture of geothermal in Britain ..." and that geothermal "to date has been seen very much as an opportunity for Cornwall and not for the UK". Stakeholders agreed that it has been difficult to get national government engaged with this technology, and while it is acknowledged that there is some interest now, the approach to geothermal and its regulation is still seen as siloed and disjointed.

While ground source heat pumps and shallow geothermal heat networks are considered in the Sixth Carbon Budget (CB6)[203] and the Net Zero Strategy[204] deep geothermal heat or power generation were not included. Recognition has improved in the last year and more recently, the Heat and Buildings Strategy[205] and the Independent Review of Net Zero[206] identify geothermal district heating as an area that needs further research in the UK. Geothermal energy received one mention in the British Energy security strategy.[207] It was further highlighted that where policy documents mention geothermal, none of them defines a clear role for geothermal in the energy transition or identifies clear targets for developing geothermal technologies as part of the UK decarbonisation and net zero efforts. This is seen by stakeholders as a key barrier for the development of a deep geothermal sector in the UK.

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[201] Abesser, C. et al. (2020). Unlocking the potential of geothermal energy in the UK. British Geological Survey Open Report, OR/20/049.
[202] Abesser, C. et al. (2023). Visualising geothermal regulations for the UK. Research brief. Unconventional Hydrocarbons in the UK Energy System (UKUH) project. Newcastle University
[203] Climate Change Commission (2020). The Sixth Carbon Budget.
[204] BEIS (2021). Net Zero Strategy: Build Back Greener.
[205] BEIS (2021). Heat and Buildings Strategy.
[206] Skidmore, C. (2023). Mission Zero- Independent Review of Net Zero.
[207] BEIS & Prime Minister's Office (2022). British energy security strategy.

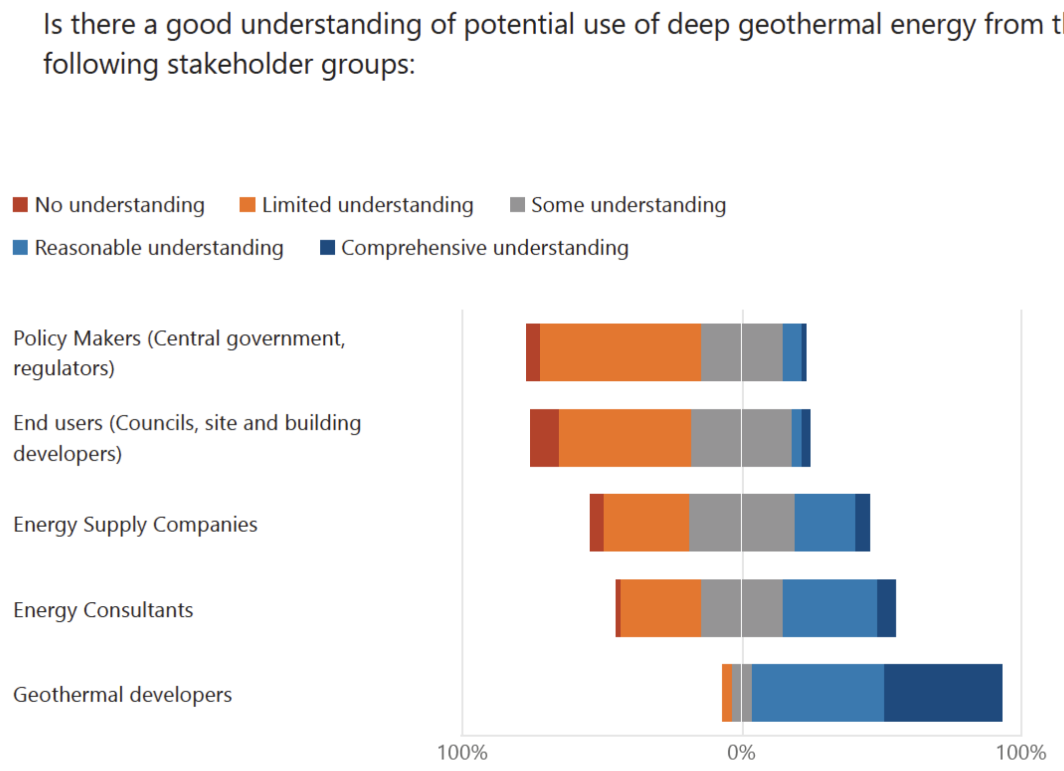

Figure 27: Stakeholder ratings of the awareness of deep geothermal technologies amongst different stakeholder groups (online survey, 59 responses, this study) (© North East LEP).

(4) *Public acceptance is perceived by most stakeholders (69%) to be average to very high while 26% considered it to be low and 5% very low.*

Experience of geothermal projects within the UK is limited. There is also very little direct knowledge on the public perception, knowledge and acceptance of geothermal technologies in the UK population relating to this technology. While overall acceptance for geothermal energy was also rated high at the UK Climate Assembly 2019[208], a recent study[209] conducted within the context of the mine water geothermal research site in Glasgow (UK Geoenergy Observatory), highlighted that awareness of geothermal technologies can be low in general. It identified three key inter-linked themes that were of most concern to the public with regards to these technologies: risk, accountability, and trust. With much debate around the potential risks involved in subsurface energy technologies, many participants also felt that they wanted more information about the benefits and risks of each of the technologies, to be involved in the decision-making process and to help them make more informed decisions.

[208] Climate Assembly UK, 2020.
[209] Dickie, J. et al. (2020). Evaluating the relationship between public perception, engagement and attitudes towards underground energy technologies. British Geological Survey Open Report OR/20/056.

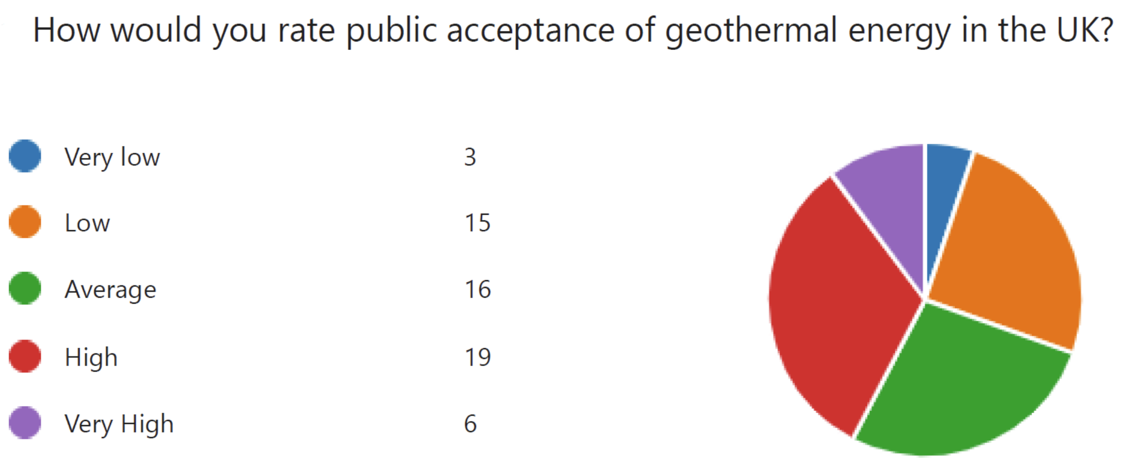

Figure 28: Stakeholder ratings of public acceptance for geothermal energy in the UK (online survey) (© North East LEP).

Northern Ireland is developing its geothermal energy policy using a social sciences-led approach to ensure that "the geothermal transition is accessible, fair, and without adverse effects on peoples' 'sense of place', their jobs and quality of life." The studies carried out have recommended linking geothermal subventions and/or incentives with community social value in developing geothermal projects. [210]Similar approaches are in use in other countries (e.g., Denmark) where energy projects are required to create social value for the local communities in which they operate.

Studies from other countries suggest that public concerns around deep geothermal projects are mostly focussed on induced seismicity[211] as well as on surface disturbances including noise, vibrations and visual impact.[212] Induced seismic risks were found to affect acceptance ratings most strongly. UK stakeholders agreed that induced seismicity is the major risk in terms of public perception and acceptance of geothermal energy projects. A recent study suggests that negative perception from shale gas fracking might have an influence on the perception of deep geothermal energy (perception spillover), influencing the conditions that deep geothermal would be expected to meet.[213, 214]

Current UK deep geothermal power projects have included an extensive community engagement and education programme that started while the projects were still in the planning stage. The project has not met any major opposition, although it was reported that perceived unfairness of the decision-making procedures adopted by actors responsible for the project led to discontent among some locals.[215] There is strong consensus amongst stakeholders that public engagement is an extremely important aspect of geothermal projects, and that ineffective public engagement by some could create a barrier for the entire industry (Figure 29).

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[210] Palmer, M. et al. (2022). Net Zero pathways: Building the geothermal energy sector in Northern Ireland. Abridged Report. NI Department for the Economy
[211] Knoblauch, T. A. K. et al. (2019). Siting deep geothermal energy: Acceptance of various risk and benefit scenarios in a Swiss-German cross-national study. Energy Policy, vol. 128, pp. 807–816.
[212] Chavot, P. et al. (2018). Social shaping of deep geothermal projects in Alsace: politics, stakeholder attitudes and local democracy. Geothermal Energy, vol. 6, pp. 1–26.
[213] Westlake, S. et al. (2023). Perception spillover from fracking onto public perceptions of novel energy technologies. Nature Energy, vol. 8, pp. 149–158.
[214] Cox, E. & Westlake, S. (2013). Perception Spillover: The impact of fracking on public perceptions of other technologies Research brief. Unconventional Hydrocarbons in the UK Energy System (UKUH) project. Newcastle University.
[215] Tirotto F. et al. (2019). Exploring attitudes toward social acceptance of the first deep geothermal technology in the UK: a qualitative study. Geophysical Research Abstracts 21 no. EGU2019-11009.

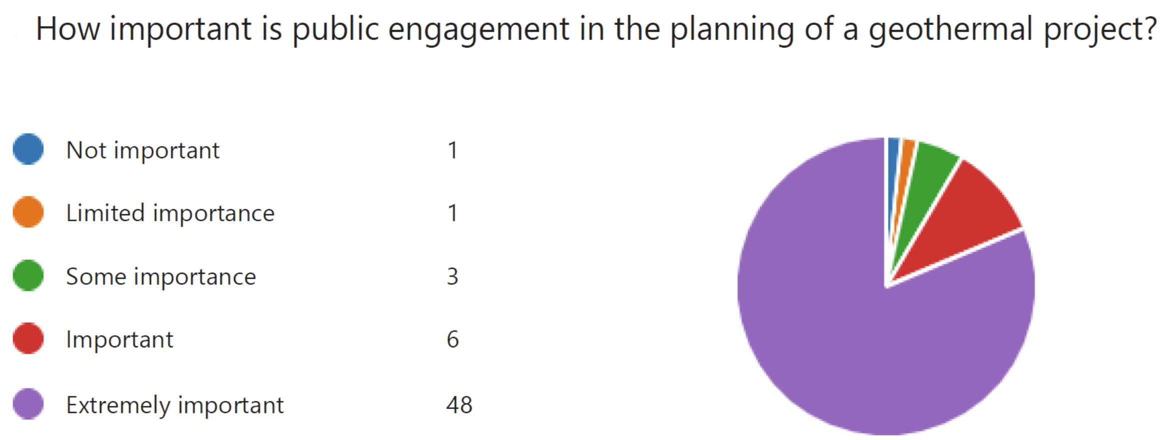

Figure 29: Stakeholder ratings of the importance of public engagement for geothermal projects (online survey) (© North East LEP).

5.3 GOVERNMENT SUPPORT AND INVESTMENT

5.3.1 Financial incentives and support for geothermal heat projects

(5) *Stakeholders reported that it is difficult to get funding for geothermal heat projects due to a lack of financial support mechanisms.*

The Green Heat Networks Fund (GHNF) is a £288 million capital grant fund for low and zero carbon (LZC) heating and cooling networks in England (new and retrofits) with an end-user demand of 2GWh/year or for a minimum of 100 dwellings in urban and rural settings, respectively. Deep geothermal is named as an eligible technology, but there currently is no case where deep geothermal has received funding under the GHNF or its predecessor – the Heat Network Investment Programme (HNIP).

Previously, the Non-domestic Renewable Heat Incentive (RHI)[216] was the principal mechanism to support non-domestic geothermal heat installations, but it closed in 2021 and has not been replaced by a similar scheme. As a result, government support for deep geothermal heat projects is only available through schemes that support public sector organisations (e.g. through the Public Sector Decarbonisation Scheme) or in conjunction with heat networks (e.g. through GHNF). Receiving funding through these schemes for deep geothermal projects has been described as difficult (see point 6)

It was highlighted by stakeholders that local councils and public sector organisations are key potential users of geothermal for decarbonising their estates, but their uptake of the technology is inhibited by the high capital costs. Furthermore, the high risks associated with deep geothermal projects make it difficult to justify the spend (under current government procurement rules) against lower risk options. The Heat Networks Delivery Unit (HNDU) provides support to local authorities in England and Wales through the early stages of heat network development, including for techno-economic feasibility – but not including drilling costs.

[216] https://www.gov.uk/non-domestic-renewable-heat-incentive

(6) *While the public sector is seen as a main potential beneficiary of deep geothermal developments, stakeholders highlighted that geothermal has difficulties with assessing the available funding mechanisms for the public sector decarbonisation.*

Dedicated funding schemes are available for the public sector to reduce their carbon emissions in line with the UK's 2050 net-zero target. For example, the Public Sector Decarbonisation Scheme (PSDS), funded by DESNZ and delivered by Salix, provides grant funding to deliver capital energy efficiency and heat decarbonisation projects within public sector non-domestic buildings in England. While geothermal is eligible in theory, stakeholders have reported that, in practice, the qualifying criteria preclude deep geothermal development from getting funding, mainly because the timeframe of 1 or 2 years (i.e. the length of PSDS project) for delivering carbon savings is not realistic for geothermal heat projects which need four years or more for emission savings to be delivered. Support is available from the Local Area Energy Plan (LAEP) DESNZ / Energy Systems Catapult programme, which provides technical, commercial and policy expertise to wide area Local Authority energy project development. In the absence of such funding, government procurement rules and processes make it difficult to justify the high spend for geothermal developments against other renewable options that are perceived to have lower risks.

(7) *Outlining the scale of the tasks, some stakeholders highlighted that a portfolio approach is needed to decarbonise the public sector estate.*

The set up and application/ decision time scales of existing grants schemes are seen as unsuitable for delivering decarbonisation of the public sector estate at scale and in line with existing targets. The need for submitting a separate grant application for each project is regarded as a hurdle to the wider decarbonisation efforts because of the time and effort required for preparing and submitting these applications.

5.3.2 Financial incentives and support for geothermal power projects

(8) *Geothermal power projects have not been successful in winning an allocation under the Contracts for Difference scheme.*

Contract for Difference (CfD) is the Government's main mechanism for supporting low-carbon electricity generation. Contracts are awarded in a series of competitive auctions. The lowest priced bids are successful, receiving (or paying) the difference between the 'strike price' (a price for electricity reflecting the cost of investing in a particular low-carbon technology) and the 'reference price' (a cost measure of the average GB market price for electricity). Under the current system, the likelihood of a geothermal bid being successful is very low because geothermal power competes against more developed technologies such as offshore wind or Advanced Conversion Technologies (ACT) and because there is no guaranteed minimum allocation for geothermal power projects.

Independent inquiries undertaken by the UK Conservative party's 1922 BEIS committee[217] and the Environmental Audit Committee[197] have called for the creation of a ringfenced fund for geothermal power projects under the Contracts for Difference scheme similar to other nascent technologies such as tidal power. Since then, BEIS (now DESNZ) has proposed amendments to the scheme for Allocation Round 5 (AR5) which opened in March 2023. Under the new rules, there is still no minimum funding for geothermal and the administrative strike price (ASP) for geothermal power has been reduced from £133/MWh to £119 /MWh which stakeholders (developers) consider less attractive. Stakeholders have also highlighted that there has been no consultation on whether this is the right level of ASP for geothermal.

[217] 1922 Business, Energy and Industrial Strategy Backbench Committee (2022). INQUIRY 2: Deep geothermal and Mine Water: Valuable new sources of low carbon heating.

They considered the previous ASP of £133/MWh as a reasonable starting point to support development of the geothermal power sector as part of a ringfenced pot for geothermal.

(9) *Overall, the support available for geothermal projects was seen as poorer compared to support given to other renewable technologies, specifically to wind and solar.*

Currently, it is difficult for geothermal energy developers to compete with the existing energy options. The lack of recognition of geothermal in government strategies makes it difficult to attract investors. Stakeholders highlighted that existing sectors receive significant subsidies and support (e.g., wind, solar) or other benefits like the Energy Profit Levy (EPL) (which is available for oil and gas production but not for geothermal). Therefore, payback times for these technologies are shorter and they are perceived as cheaper as their levelised cost of energy (LCOE) does not reflect the true cost of heat/electricity generation, but a subsided rate. Clear long-term consistent support is required for geothermal projects in order to improve investor confidence in what will be long-term investments.

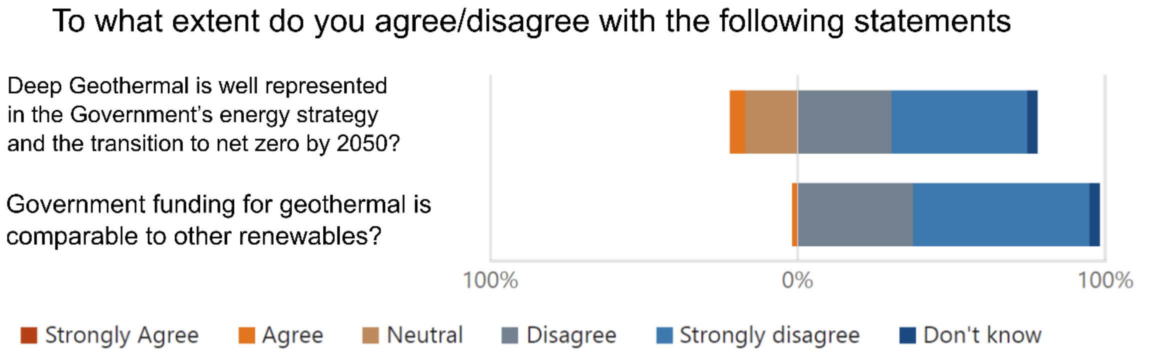

Figure 30: Stakeholder ratings of geothermal recognition in government policies and availability of funding compared to other renewable technologies (online survey) (© North East LEP).

5.3.3 Legislative support

(10) *Participants have identified a lack of legislative support relating to low-carbon heating in buildings as a potential challenge for the wider adoption of low-carbon heating technologies, including geothermal, in existing and new buildings.*

Such measures have been successfully deployed in the car industry. The legal phase out date of new petrol and diesel cars from 2030, for example, together with the impending introduction of Zero Emission Vehicle (ZEV) mandate (regulation that requires vehicle manufacturers to sell a minimum number of zero emission vehicles as a proportion of their overall UK sales) from 2024 is seen to have caused a significant shift in the automotive industry with several vehicle manufacturers announcing changes to the types of vehicles that they will be producing.[218]

The UK Climate Change Committee has recommended that from 2025 all new homes be fitted with low-carbon heating. Such measures, including banning installations of fossil fuel fired heating systems in new and retrofitted homes, have recently been introduced in Belgium, Germany, and the Netherlands. The UK Government has announced plans to introduce a new Future Homes Standard and Future Building Standard in 2025. Among the requirements, there will be a stipulation that new homes must be "zero carbon ready".[219] Stakeholders regard the current absence of such legislative measures as a potential challenge for the wider adoption of low-carbon heating technologies. Until details of the policy have been announced and passed into legislation it will remain unknown to what

[218] Edwards, H. et al. (2023). Electric vehicles and infrastructure. House of Commons Library.
[219] Pathway to the Future Homes and Building Standard: June 22, Spring 2024 & 2025.

degree these measures will encourage deep geothermal developments. Other planned legislative measures like the "Clean Heat Market Mechanism" (CHMM), aimed at supporting the transformation of the heating appliance market, are unlikely to have a measurable effect on deep geothermal.

(11) *Space heating and heat networks are seen by stakeholders as the main application for deep geothermal in the UK but there is a risk that geothermal will be overlooked due to a lack of recognition in current heating policies and legislation.*

For example, geothermal is not considered in the new heat network zoning framework that was announced in the Government's 2020 Energy White Paper[220] and is currently being piloted in England. It entails the identification and delineation of low-carbon heat sources which can be readily connected to a low-carbon heat network. Mandating connection for certain categories of buildings to heat networks could provide enough customers to remove the uncertainties for geothermal developers around future demand,[221] which has caused failure of some geothermal developments in the past. However, the current framework in England is focussed only on identifying waste heat source for supplying heat networks. Including geothermal sources in such frameworks (and similar approaches that are planned in Northern Ireland and Scotland) is seen as imperative for the wider recognition of geothermal opportunities in the UK and their role in the decarbonisation of heat. The inquiry by the 1922 BEIS Backbench Committee[217] suggested that the (DLUHC) "could encourage local authorities to consider geothermal resources when assessing local energy needs, particularly for new housing developments."

5.4 DATA AVAILABILITY AND ACCESSIBILITY

(12) *Participants have identified a need for improving availability and accessibility to subsurface data to progress the sector, including information about available geothermal potential. Lack of data and access is seen as a barrier by developers and by potential clients/ users, specifically with regards to identifying feasible areas for geothermal development, but also because it limits awareness of the geothermal opportunities that exist across the UK.*

Subsurface data, in particular seismic reflection surveys and borehole data are vital when carrying out comprehensive assessments of both geothermal opportunity and risks for these developments.[222] Cost of acquisition of such data can be high (Chapter 2), so use of existing data is often the only mechanism for initial site selection.

Currently, relevant data for geothermal projects sit across a range of organisations and can be difficult to access.[223] Most onshore seismic reflection datasets are available under licence from the UK Onshore Geophysical Library (UKOGL) (https://ukogl.org.uk/map) – which is a charity. The regulator for oil and gas – the North Sea Transition Authority (NSTA) – previously the Oil and Gas Authority (OGA) hold other data and information that may be transferable to geothermal. Data acquired to support the hydrocarbon industry fall under hydrocarbon regulations which include data-reporting requirements, with clear confidentiality periods that determine when archived data can be released to the public domain. Offshore data are subject to the same regulation and are available through the National Data Repository (NDR) (https://ndr.nstauthority.co.uk/).

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[220] Department for Business, Energy & Industrial Strategy (2021). Proposals for heat network zoning. GOV.UK.
[221] Heat and the City (2019). Meeting strategic challenges of UK district heating. Briefing: March 2019.
[222] Ireland, M. et al. (2021). Suitability of legacy subsurface data for nascent geoenergy activities onshore United Kingdom. Frontiers in Earth Science, 9,
[223] Dickinson, A. & Ireland, M. (2022). Digging into data access: The need for reform. Geoscientist, Summer 2022, pp 32–37.

Such data-reporting requirements do not exist for other sectors, including geothermal, and as a result, data availability and access are more difficult. There is no obligation for companies to share their data. The lack of publicly available data and data sharing obligations is seen by many stakeholders as holding back the sector. It is also seen as a challenge for a potential geothermal regulator who would require such data and information to formulate a regulatory approach and/or make decisions about individual systems.

The British Geological Survey (BGS) has a mandated role to provide geological data and to act as the agency responsible for providing subsurface data to the UK government. It holds legacy data sets such as the Geothermal Data Catalogue (GDC)[96] which contains data from a range of public and private sources and includes measurements derived by different methods.[224] The geothermal legacy data from the GDC has not been publicly released by the BGS. Ownership of the data is governed by a range of legal mechanisms, some of which refer to organisations and companies that no longer exist and where historical confidentiality periods are unclear. In addition, there are concerns that variations in data quality and measurement accuracy are not adequately captured within the historical data set – hence constraints around data quality are not visible to potential users of this data set. BGS is currently undertaking a programme of work to validate and verify the GDC data with the aim of making an improved data set available, including qualifiers relating to provenance and accuracy of the data.

5.5 UK GEOTHERMAL SUPPLY CHAIN

(13) *Parts of the supply chain exist but are not coordinated because there are currently too few UK deep geothermal projects.*

Figure 25C suggests that drilling skills and equipment are thought to be available and geothermal technologies are sufficiently mature for deployment for geothermal heat and power generation. However, lack of an established supply chain has been seen by some stakeholders as a barrier to uptake of geothermal systems and has been identified as adding time and costs to projects currently in development. There are opportunities for skills and supply chains to be adopted from the oil & gas sector, and current geothermal projects are already making use of these, where appropriate.

(14) *The importance of having a pipeline of projects was stressed by several stakeholders to help develop skills, generate momentum for the industry and engage the supply chain companies, as well as to encourage investment.*

These projects are considered important to reduce the risk profile of the industry and overcome the perception that the industry is immature. The EAC stakeholder workshop and previous engagements[225,226] have concluded that the UK needs demonstrators of geothermal installations as well as heat supply schemes in order to prove the economic model and demonstrate the full supply chain of delivering heat to users. Demonstration projects that showcase the technology are seen as a way to reduce uncertainty in both subsurface and technology. They deliver geological, technical, business, and finance models along with an understanding of the relationship between them. Pilot projects can serve as educational and public engagement tools. They provide data on carbon savings and return on investment that could encourage other projects, thereby stimulating demand in a way that mobilises the supply chain.

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[224] Busby J et al. (2011) The measured shallow temperature field in Britain. Q J Eng Geol Hydrogeol.; 44:373–87.
[225] NERC, University of Strathclyde & BGS (2019). Record of proceedings UK Geoenergy Observatories Glasgow Geothermal Energy Innovation Workshop.
[226] Palmer, M. et al. (2022). Net zero pathways: Building the geothermal energy sector in Northern Ireland. Department for the Economy. Technical Report, pp. 1–136.

As highlighted in feedback from consultations commissioned by Scottish Enterprise,[227] "the supply chain won't develop until there is demand for geothermal energy in Scotland/UK". Despite this, there is a significant number of both active and potential companies in the UK that could serve the key supply chain elements (Figure 31) and form the basis for economic activity in the geothermal area, given the right stimuli.

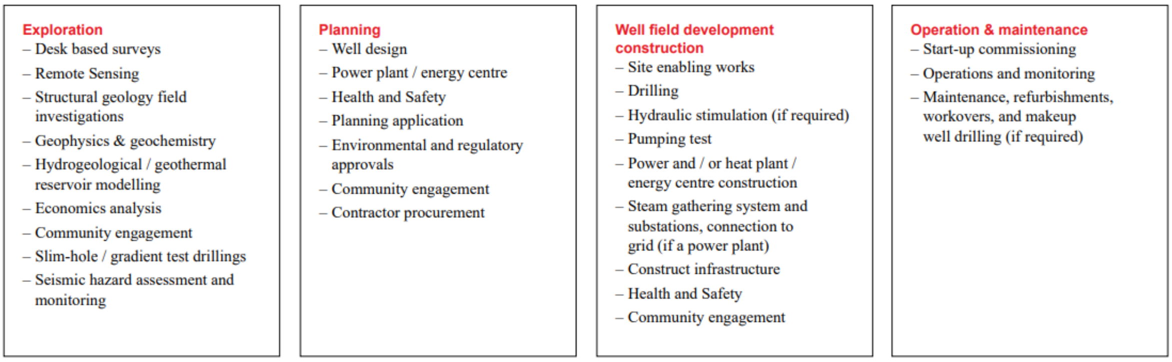

Figure 31: Key supply chain activities for deep geothermal projects (© Arup).

5.5.1 Seismic acquisition

(15) *According to stakeholders, the UK supply chain for seismic acquisition has been reducing since 2016, with only a minimum level of skills and capacity retained in the UK.*

There is some capacity in the UK to undertake small acquisitions but for larger surveys the industry currently has to rely on expertise and equipment from Europe. This adds costs and time to existing projects. UK service providers highlighted that existing capacity can be built up, but they needed a minimum of 2–3 consecutive projects and a minimum of two months of work for making their re-engagement in geothermal data acquisition worthwhile.

5.5.2 Drilling rigs

(16) *Recent geothermal drilling in the UK has used (specialist) drilling rigs from Europe (UK rigs were not suitable for drilling in that geology and to the required depth).*

According to stakeholders, there are two geothermal drilling rigs available in the UK and a further 13 rigs in Europe. In addition, there are four oil & gas drilling rigs in the UK with capability to drill to the depths needed for geothermal direct-use projects (typically 1 km to 3 km deep). With less drilling onshore, however, companies are unlikely to replace aging drilling equipment or invest in new ones unless there is reassurance that a pipeline of deep geothermal project exists that would justify their investments. Stakeholders highlighted that, currently, there is no incentive for oil and gas drilling companies to transition to geothermal. However, the downturn in the oil and gas sector was seen as beneficial for geothermal projects as it means that there is no shortage of skills or personnel for drilling. Stakeholders highlight that, as demand for geothermal in Europe increases, UK access to drilling rigs could become an issue.

5.5.3 Components and materials

(17) *Stakeholders highlight that a service industry for geothermal is not available in the UK.*

Components and parts for UK geothermal drilling and wells are largely sourced from the existing oil and gas supply chain, or from abroad. With deep geothermal drilling focused in Cornwall, being located on the opposite end of the country to the oil and gas sector, which is

[227] OPTIMAT (2019). GGERFS Company Demand Analysis, FINAL REPORT Scottish Enterprise, J3120.

heavily based in Aberdeen, current projects have highlighted costs and time implications of having to source even small items from that distance.

Stakeholders also reported that the supply chain has been impacted by COVID-19 as well as by Brexit. Customs and visa requirements for equipment and personnel coming from Europe has resulted in more paperwork and costs as well as in extended procurement periods.

5.5.4 Government demonstrators

(18) *To build confidence and re-engage the supply chain, stakeholders proposed visible government geothermal demonstrators at key government infrastructure (e.g., hospitals, government buildings, schools), thereby also contributing to the decarbonisation of the public sector.*

In Northern Ireland, two geothermal demonstrator projects have been commissioned by the Department for Economy, who is responsible for energy policy in NI, including one study focussing on the deep geothermal targets. The study aims to promote uptake of geothermal technologies in the agri-food sector. It will include geophysical surveys to gather the subsurface data needed to assess the resource and select a drill site for a deep geothermal well.

5.6 TECHNOLOGY

(19) *Technology readiness and skills for drilling and the installation of geothermal heat and power projects are considered to be high and available (Figure 25C) but innovation in drilling is seen to be urgently needed to reduce project costs.*

Drilling is the most expensive element of a geothermal project. With standing times for drilling rigs of £40k/day, technology innovation for faster, more efficient drilling and well completion is seen by most stakeholders as a priority for innovation. There are several active projects around the world developing new drilling technologies, including potentially disruptive and new drilling technologies, such as Millimetre Wave Technology (see Chapter 6).

Other areas where technology innovation is needed include the conversion of oil and gas wells for geothermal uses (see Chapter 4).

5.7 REGULATION

(20) *Participants highlighted that geothermal energy is not recognised as a natural resource and that this leads to uncertainty in the status, ownership and regulation of geothermal energy.*

Responsibilities for regulation of deep geothermal systems are currently split between different authorities including local planning authorities, environmental regulators and Health and Safety Executive (for deep drilling). With only a few deep geothermal systems currently in development, the regulatory system has not been fully tested. However, many participants (20 out of 38) who responded to the corresponding survey question (Figure 32) have found the regulatory requirements for deep geothermal project to be somewhat difficult or extremely difficult. The Scottish Government has development regulatory guidance for the development of deep geothermal projects in Scotland.[228]

In the workshop and also in a previous study,[229] stakeholders reported that the absence of a coordinating body for the geothermal application process resulted in long time scales for

[228] Scottish Government (2017) Regulatory Guidance: Geothermal Heat in Scotland
[229] Abesser, C. et al. (2023). Visualising geothermal regulations for the UK. Research brief. Unconventional Hydrocarbons in the UK Energy System (UKUH) project. Newcastle University.

permitting and regulation. This is seen by stakeholders (industry) as a barrier to faster roll out of geothermal projects. Many participants would like to see a single, centralised regulator or a coordinating body that could help developers to navigate the permitting process. Some suggested the Coal Authority or the North Sea Transition Authority (NSTA) as potential regulators for geothermal. It was highlighted that, although the NSTA has experience in regulation of a similar resource (i.e., oil and gas), it currently has not been given the remit (or legal basis) for regulating geothermal energy. Hence, the NSTA would require direction from the responsible government department, i.e., the newly formed Department for Energy Security and Net Zero.

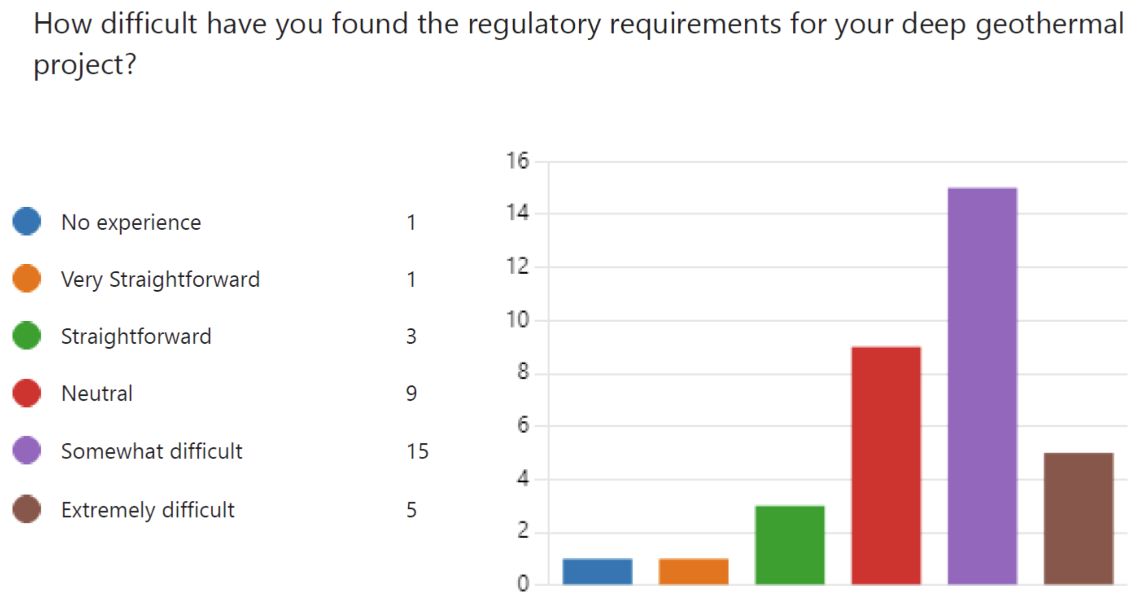

Figure 32: Stakeholder ratings for the regulatory process for deep geothermal projects (© North East LEP).

In a previous study,[229] participants reported that some of the HSE regulations (taken from oil and gas regulation) were regarded as less applicable to geothermal systems in the UK and seen to add unnecessary costs and time to already very tight projects.

Introduction of a licensing system is seen as important by stakeholders as it offers insurance to investors. It would also enable regulators to impose conditions on operator relating to community engagement requirement or data sharing commitments. However, it is recognised that a critical mass of projects is needed before licensing is introduced.

5.7.1 Environmental impacts

(21) *Environmental impacts were considered low by stakeholders of this and previous studies.[229] Risk are considered to be well-covered by existing regulation, although some inconsistencies were identified that should be addressed.*

Considering the state of development of deep geothermal in the UK, there was consensus amongst stakeholders that it is too early to assess the effectiveness of regulation. The regulators acknowledge that the environmental regulations weren't formed with geothermal in mind, but in their view, regulation is adequate and it is not clear, at this point in time, what additional regulation for geothermal would be required.[229] However, it is seen as important to gather project experiences and operational data early on and to develop best practice guidelines for deep geothermal that can then be adopted by local authorities in all parts of country.[229]

There is consensus that induced seismicity for geothermal projects needs to be regulated, but the current system in place for geothermal is seen as adequate by the industry. The industry acknowledges that the occurrence of induced seismicity is an important consideration in some geologies and that it is difficult to precisely model and predict, and hence there remains a small risk of triggering seismic events during all stages of geothermal project development and operation that needs to be mitigated against and managed.[229] There is a preference for a ground velocity based regulation model, as operated by the schemes in Cornwall, rather than a magnitude based approach.

Preparation of management and mitigation protocols specific to the deep geothermal industry can reduce the risk of high levels of seismic activity. Monitoring is important to demonstrate that regulations are being effective to identify adverse effects and inform appropriate management response.

It was also recognised that induced seismicity is a key risk for geothermal projects in terms of public perception and acceptance. Clear regulation and engaging early with the public on hazards and risks and how they are being managed will help gain public trust and acceptance of this technology. Public acceptance is considered more important at present for the success of the industry than the details of the regulation itself, including the terminology used which is seen to be crucial in determining how the public perceives the regulatory protocol.[229]

Some stakeholders also perceived inconsistencies in the way environmental regulation is applied to geothermal projects across the country. There was also the perception by operators in other industries that rules for geothermal energy are less stringent than for other extractive industries.

6 Building a UK deep geothermal sector

6.1 INTRODUCTION

There is wide consensus amongst stakeholders that there are viable geothermal prospects and that potential exists across the UK for developing geothermal energy projects, especially for geothermal heating (Chapter 5).

Experiences from other European countries, including France, the Netherlands, Germany (Bavaria), Switzerland and others[14] has shown that market development is most successful in countries where long-term government commitment and financial support are available. There are some country-specific drivers that have enhanced the opportunities for the development of a geothermal sector in these countries. In the Netherlands, for example, large heat demands from horticulture and loss of public acceptance for gas developments have precipitated the decision to develop geothermal heating projects. In France and Germany, wide-scale availability of district heating networks has been very beneficial for geothermal projects, especially in the Paris Basin and the Molasse Basin (Munich), respectively, where most of France's and Germany's deep geothermal activities have taken place to date.

Opportunities for geothermal horticulture or district heating also exist in several areas of the UK (Chapter 4). A main opportunity for UK geothermal sector development is seen to be the decarbonisation of the public sector estate. Large buildings like hospitals, prisons or army barracks provide ideal anchor loads for geothermal heating projects as well as for district heating networks and are attractive to geothermal developers because of the potential for obtaining reliable, long-term heat purchase agreements. The public sector is identified as, potentially, one of the largest beneficiaries from geothermal developments in the UK. Some stakeholders proposed that funding should be prioritised to support geothermal heat projects or to focus on decarbonising the public sector, including the National Health Service (NHS) and large social housing projects. While opportunities for geothermal heating are seen as a clear priority, it is important to note that geothermal power projects also have an important role in developing the UK geothermal sector.

6.2 APPROACH

Stakeholder evidence collected from a range of sources,[32,33,34,36] including the stakeholder engagement undertaken as part of this study, has highlighted the challenges that the industry is facing (Chapter 5). Using this evidence together with findings from Chapter 2 (Landscape review), we identified policy measures that have been used in other countries and considered how they might address the barriers identified in Chapter 5. The purpose of this exercise was to identify potential policy options for supporting the sector development in the UK. Identified linkages between barriers and policy measures are summarised in Figure 33. A condensed review of barriers and linked policy measures is provided in Appendix 3. The effectiveness of the identified policy measures within the UK context was not investigated in this study and will need further consideration.

An attempt was made to identify the preferred policy measures and determine their prioritisation using inputs from the various stakeholders (as listed in the acknowledgements). Whilst there was strong agreement that deep geothermal energy needs more visibility in government strategies, stakeholder views differed with regards to the prioritisation of other policy measures. This meant that there was no consensus on which are the most important policy measures in the near term.

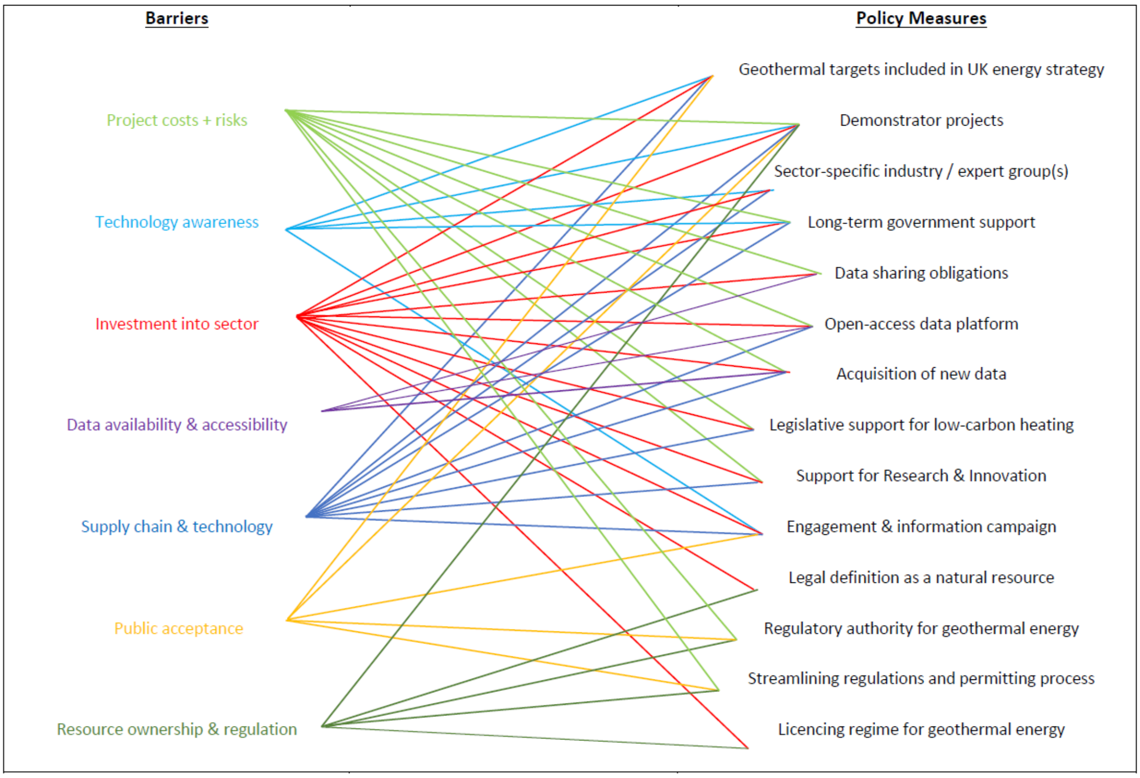

Figure 33: Linkages between identified barriers and potential policy measures for building a deep geothermal sector in the UK.

Based on the evidence collated throughout this study, we have developed a set of recommendations that could support the development of a geothermal sector in the UK, using the short-term, medium-term and long-term framework of Figure 34.

Measures identified as *short-term* are aimed at building the sector during the early stages of market development. They should be considered a priority for immediate development and implementation within the next five years. Measures identified as *medium-term* are aimed at supporting the scaling up of the sector following an initial period of market growth. They are expected to become important within the next 5 to 15 years when the technology has been proven by a range of pilot projects, and project risks have decreased to a level where the technology will be adopted more widely. *Long-term* measures are those that support the sector once the geothermal market is established (in 15 years or more) to enable its continued growth until the market is fully matured.

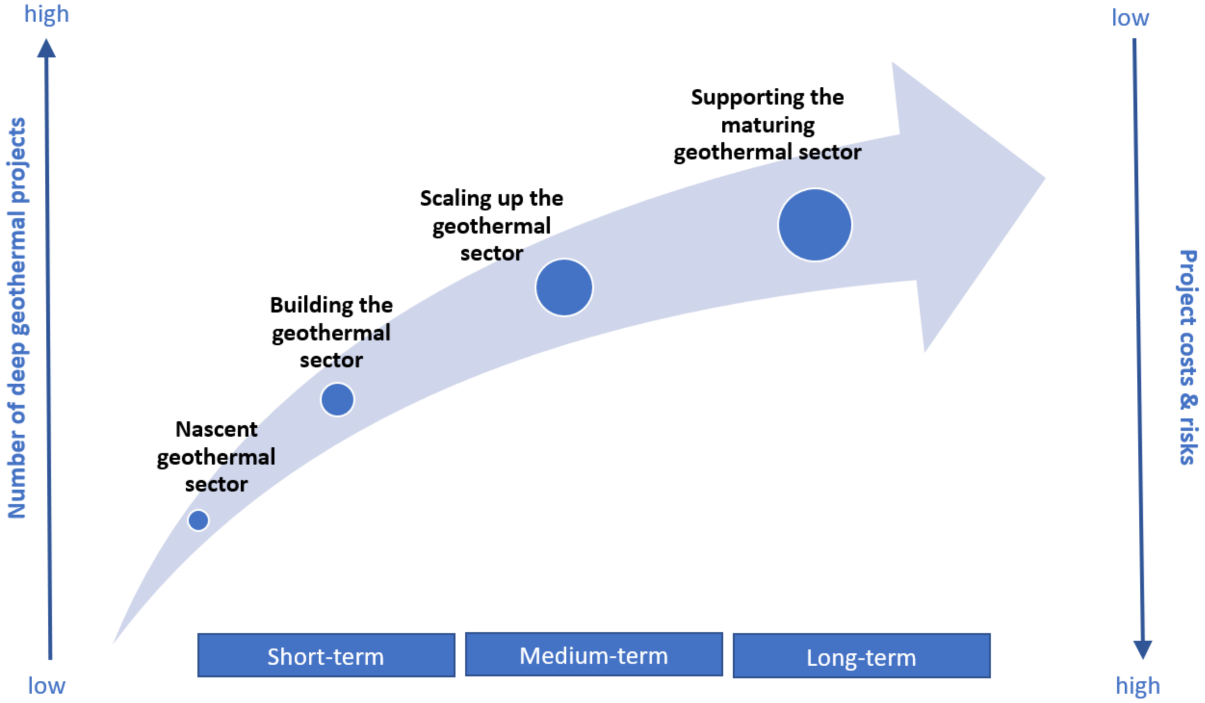

Figure 34: Route to developing a geothermal sector in the UK in the short-term (< 5 years), medium-term (5-15 years) and long-term (>15 years) (© North East LEP).

6.3 RECOMMENDATIONS

The geothermal sector in the UK is at an early market stage, where technology visibility and investor confidence are low and where sector specific public support is needed to build a pipeline of successful projects that showcase the technology. The experience in other European countries has shown that government support is particularly important during the early market development stages when technology awareness and investors' confidence is low.

6.3.1 Recommendation 1: Review of financial support for geothermal energy

In the UK, existing policy schemes offer only very limited funding opportunities for geothermal heat or power projects. Current pilot projects have taken many years to develop, during which time funding models have continually changed. This has increased project risks and limited the ability of the industry to demonstrate its viability. The Stoke-on-Trent project, for example, initially relied on the availability of the RHI and has now been put on hold until alternative funding can be identified.

A review of the available incentive schemes for geothermal energy is recommended as well as consideration of new schemes that could support the development of a self-sustaining sector. This should include a **review of existing funding for public sector schemes** for heat projects with view of identifying adjustments that would facilitate funding of public sector geothermal projects.

Providing incentives for geothermal heating projects and for public sector decarbonisation is seen as a priority by many stakeholders. However, geothermal power projects and cascading heat use also have an important role in developing the sector, and incentives should reflect this. Incentives should be guaranteed for a sufficient length of time to build investor confidence and provide assurance that incentives can be relied upon for the longer term to match their long-term investment profile. The level of support should be considered against other renewable technologies to create a level playing field. Stakeholder responses from our online survey suggest that government investment of £100 million or more may be needed to develop the geothermal sector. However, there was no clear consensus amongst stakeholders on which policy support measures to prioritise in the near term.

It is not within the scope of this report to develop recommendations for specific funding support mechanisms. From the geothermal landscape review (Chapter 2) and from stakeholder engagement, we have identified support mechanisms that have been used in other countries as well as the mechanisms that the industry would like to see deployed in the UK. A summary of different financial support mechanisms is provided in Table 8. According to Dumas et al. (2019),[230] support mechanisms should be adapted over time to reflect market maturity (Figure 35).

Short-term:

1. Measures should be designed to encourage rapid technology uptake and the development of pilots. Examples of such measures could include Feed-in-Tariffs (FiT) or Contracts for Difference (CfD) with funding ringfenced for geothermal technologies. An example of a successful policy measures is the Stimulation Sustainable Energy production scheme (SDE+) in the Netherlands (Box 2).

Medium-term:

2. As the market develops and several geothermal pilot projects are operational, measures should be introduced that support the scaling up of technology deployment. Examples of such measures could include finance mechanisms, such as rolling funds, that enable development of multiple projects in parallel rather than funding that is delivered on a project-by-project basis.

Long-term:

3. As the market matures, mechanisms should be adapted to support continuous growth until the market is fully matured, e.g. by providing a combination of (reduced) tariffs combined with risk sharing schemes. Examples of such measures include a combination of Feed-in-Tariff and a geothermal insurance scheme to cover drilling risks (Dutch model) or a loan scheme with risk sharing options for drilling (German model).

As shown in Figure 36, associated costs for such support will be high initially but then decline as the market matures.

[230] Dumas, P. et al. (2019). Risk Mitigation and Insurance Schemes Adapted to Geothermal Market Maturity: The Right Scheme for my Market. European Geothermal Congress 2019, The Hague, The Netherlands.

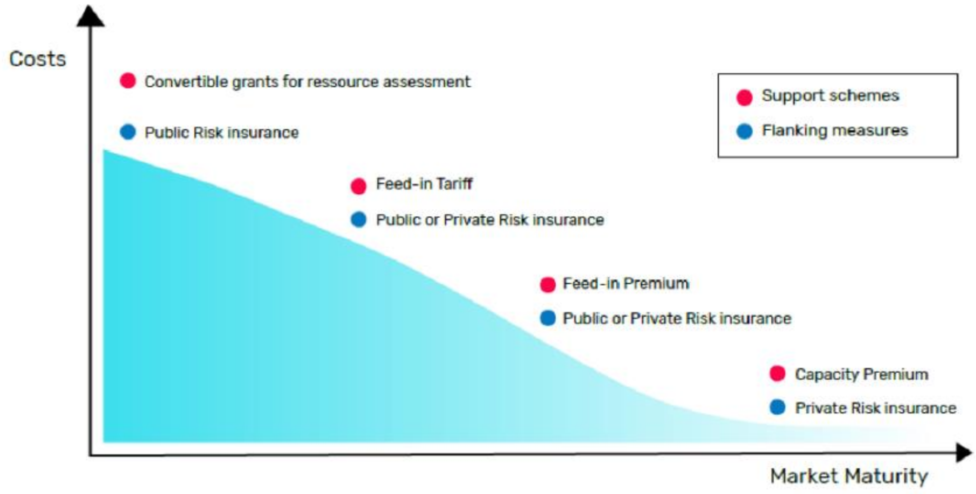

Figure 35: Support schemes for Geothermal adapted to technology maturity (from Dumas et al., 2019)[230]. Reproduced with permission from EGEC.

Financial support for the development of demonstrator projects could be beneficial in the short to medium term as they can deliver multiple benefits including showcasing the technology and raising awareness. Where information is openly shared, such pilot projects can also have an important role in developing technical, organisational, and administrative experience.

In Belgium and the Netherlands (Chapter 2), government investment in pioneering projects has helped to lay the foundations for subsequent developments of the sector. The Masterplan for Geothermal Energy in the Netherlands[231] includes a commitment from government to play an active role in demonstration projects and to support one pilot per year (for different geothermal technologies) during the initial phase (5 years) of sector development.

Stakeholder responses from our online survey suggest that a minimum of five demonstrators should be supported in the UK. Some stakeholders have highlighted the importance of setting up demonstrators for the different geothermal technologies.

Table 7: Comparison of direct policy support mechanisms for geothermal energy projects.

Mechanism	Advantages	Disadvantages	Comments/ Examples
Feed-In Tariff/ Premiums	Rewards successful projects (limits risk to funder) Can be used to reward carbon savings (Example SDE++ tariff Netherlands)	Needs continuous administration and annual re-calculation throughout payment period of subsidy. Does not address early project risks	Successful examples include the now closed Renewable Heat Incentive Scheme (GB) and the Netherlands SGE++ tariff (see Box 2)
Investment bonds, loans and grants	Upfront capital grants (one- off payments) are easy to administer.	Payments must be sufficiently high to attract uptake. They may fund unsuccessful projects.	Germany runs a successful loan scheme with risk mitigation.

[231] EBN (2018) Master Plan Geothermal Energy in the Netherlands.

	Option to combine loan and risk mitigation (Example Germany) Bridges gap between upfront investment and first returns.		Switzerland provides example of both successful and unsuccessful implementation of grant schemes.
Insurance/ guarantee schemes	A range of mechanism available (see Boissavy, 2020)[232] Addresses early project risks, including one of the largest challenges for Geothermal technologies: high geological and financial risk.	Some funds spend on unsuccessful projects. Coverage and premiums must be attractive to target users. Only sustainable if many projects are applying.	France operates a very successful geothermal insurance scheme (see Box 4). Denmark's scheme failed because application and reporting requirements were considered too complex.
Contract for Difference	Rewards successful projects (no risk to funder). Provides a guaranteed revenue for diverse renewable generation over a large market.	Scheme needs careful management and administration (including ringfencing) to prevent unfair competition. Does not address early project risks. Certainty on price only becomes clear once the CFD lots are bid.	Geothermal electricity in the UK is supported under the CfD Scheme but has not been successful to date.

6.3.2 Recommendation 2: Signposting the role of geothermal in UK net zero efforts

Clear signposting of the role that geothermal energy could play in the UK's decarbonisation efforts has been identified by many stakeholders as a key priority for the UK geothermal sector (Figure 36). Clear targets and strategies for achieving them are seen as providing confidence to the industry and supply chain, and with the right support measures, could also encourage transitioning of skills from the oil and gas sector.

Government signposting and setting targets was shown to play an important role in the development of offshore wind in the UK.[233] In the Netherlands, the publication of a national strategy[231] that sets out the Dutch government's expectation and targets for geothermal heat production has been instrumental in progressing the geothermal sector. The targets were developed based on a good understanding of the geology and knowledge of the extractable geothermal resource, derived from shared exploration and operational data available via the public data platform ThermoGIS.[63]

Short-term

1. We recommend that consideration is given to **how visibility of geothermal energy technologies could be improved** in UK government strategies and what role technology-specific targets could play in attracting investment into geothermal projects and encouraging engagement of the supply chain.

[232] Boissavy, C. (2020). Report reviewing existing insurance schemes for geothermal, GEORISK;
[233] The Economist (2022). Why Britain is a world leader in offshore wind

Long-term

2. As more geothermal projects come online and operational data becomes available, a better understanding of the economically useable geothermal resource will develop which will enable **the definition of long-term targets for the sector**. Measures to improve data availability, accessibility and sharing (as outlined in Recommendation 3) could accelerate the improvement in our understanding of the subsurface and the available geothermal resource, thereby supporting the formulation of geothermal targets.

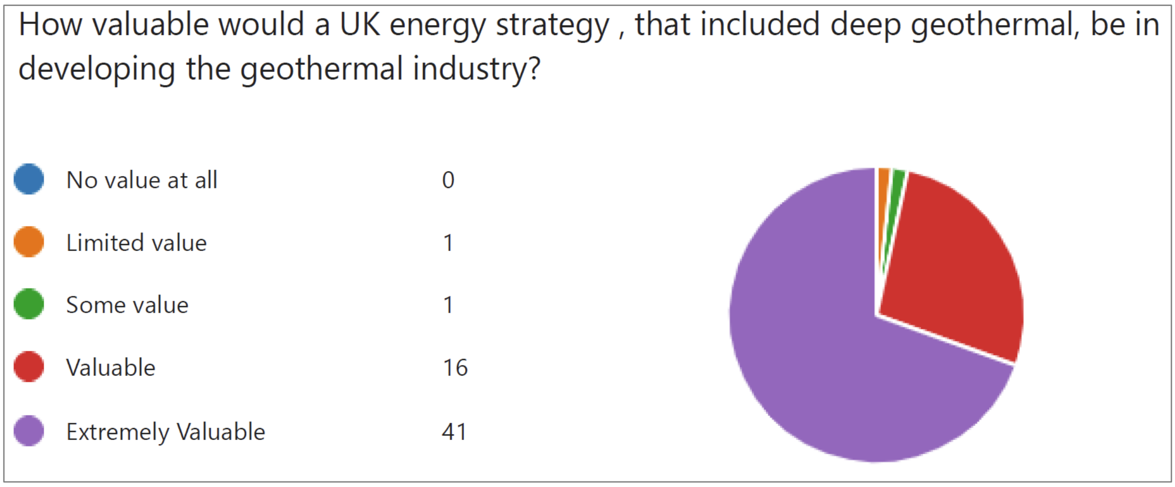

Figure 36: Online survey votes on the value of including geothermal energy in the UK Energy strategy for developing the sector (© North East LEP).

6.3.3 Recommendation 3: Improve data availability and accessibility

Like other sectors,[234] the growing geothermal sector will require greater access to timely and transparent data, including seismic reflection and borehole data, which are essential for identifying and assessing geothermal opportunities and risks.

Stakeholders suggested adopting the model of a dedicated publicly available database like those available in the Netherlands (ThermoGIS[63]) and Germany (geotIS[235]). Funding for developing and maintaining these tools has come from different sources. GeotIS, for example, was developed since 2006 in several 3-year projects funded by the German Government.[235] ThermoGIS was developed with funding from the EU and the Dutch Government.

In addition to data access, UK stakeholders also mentioned the need for maps and tools to highlight where geothermal opportunities exist across the country for developing geothermal heat or power projects. In Germany, the Bavarian Geothermal Atlas[236] was regarded as an important supporting factor for the extensive geothermal developments in Bavaria. It shows where favourable conditions exist for the exploitation of geothermal heat or electricity generation, including detailed maps and data of depths, thickness, and temperatures of the geothermal target.

Geothermal developments in Bavaria were further supported by continuous collection of subsurface data from seismic campaigns (e.g. through the GRAME project funded by the Federal Ministry of Economics and Energy[237]) and drilling which has considerably improved

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[234] Wood (2014) UKCS Maximising recovery review : final report
[235] geotIS website: https://www.geotis.de/homepage/project_history
[236] Bayerischer Geothermieatlas (in German)
[237] GRAME project

the understanding of the geothermal resource and reservoir. The timeline of geothermal development in the area[14] shows a marked rise in geothermal installations following the availability of the first 2D seismic data for geothermal.

We recommend that consideration is given to **improving data availability and accessibility for the geothermal sector.** Several measures have been raised by stakeholders and found to be important, including availability of a single, open-access data platform, data sharing obligations as well as a government-supported exploration programme. Further engagement is necessary to clarify how these might be implemented and what overall impact they will have on the sector.

Short-term

1. As cost of data acquisition can be very high (Chapter 3), use of existing data is often the only mechanism for initial site selection for many geothermal projects. Currently, relevant data for geothermal projects sit across (and are owned by) a range of organisations and can be difficult to access.[238] Legacy data sets often lack details relating to data provenance and quality, which has prevented their release for open use. To maximise the value and enable open sharing of this data, we recommend that consideration is given, in the short-term, to supporting **the review and processing of legacy data** and the development of formats through which validated data sets can be made openly available and shared. This will directly enhance the availability of data relevant for geothermal projects.

Medium-term

2. In the medium-term, to enhance data accessibility, we recommend that consideration is given to the **development of a single data platform** through which these validated, publicly available data sets (recent and legacy) and geothermal information can made available to stakeholders and the public.

Long-term

3. As utilisation of geothermal energy increases, acquisition of new data will be needed to identify future geothermal opportunities in areas where less data and subsurface knowledge are available. **Government supported exploration programmes** could be used to fill in subsurface data gaps in key areas (see Chapter 3) to accelerate the development of geothermal energy (and delivery of associated benefits). Such programmes were successfully implemented in the past – e.g. the UK Government provided £20 million for seismic data acquisition in 2015 to revitalise UK Offshore Oil and Gas exploration.[239]
   A dedicated data acquisition programme (SCAN[240]) consisting of 1,800 km of 2D geophysical surveys was undertaken in the Netherlands in target areas to provide up-to-date and location-specific data of the potential geothermal targets to support the identification of drilling targets. It formed part of the research phase of their geothermal strategy and focussed on areas where there was no, or insufficient data about the subsurface. Government support for acquiring such surveys was identified by many stakeholders as an important step in progressing the geothermal sector in the UK.

[238] Dickinson & Ireland (2022). Digging into data access: The need for reform. Geoscientist, Summer 2022, pp 32–37.
[239] James (2016): Oil and Gas Authority – Information & Samples
[240] NLOG SCAN project site https://www.nlog.nl/en/scan

4. Whilst Government may choose to play a role in data collection (Recommendation 3.3), there also needs to be **wider sharing of data** across the sector to reduce risks and costs and maximise the benefits of the available geophysical and geological data – private or public. This could be achieved through **the introduction of data sharing obligations**. Such obligations already exist in other sectors. In the UK oil and gas sector, for example, data sharing is mandated as part of the licensing conditions, but other data sharing models could be considered. For example, Germany's Geological Data Act[241] mandates that all data and results from all geological investigations are made available to the national geological authority within three months of collection. The national geological authority and the state geological surveys, in return, are responsible for collecting and securing geological data and making it available to the public to ensure the sustainable use of the subsurface.

6.3.4 Recommendation 4 – Review of legal status and regulation of geothermal energy

With only a few systems currently in development, the UK regulatory system for deep geothermal has not been fully tested. Existing regulations are broadly regarded as adequate for the current level of geothermal deployment.[229] However, the absence of a coordinating body for the geothermal application process is seen by stakeholders as a barrier to faster roll out of geothermal projects, and many stakeholders have found the regulatory requirements for deep geothermal projects to be somewhat difficult or extremely difficult (Figure 32).

The undefined legal status of geothermal energy means that ownership of the geothermal heat cannot be defined or licenced. It also means that there is currently no regulatory body with a remit for managing the UK geothermal energy resources. This has an impact on some geothermal activities such as the reuse of hydrocarbon wells. The North Sea Transition Authority (NSTA) is stretching their existing remit to accommodate investigations into the repurposing of wells. However, it is unclear if and how the NSTA will be able to issue licences for a resource that is not legally recognised and not within their oversight.

Geothermal energy is recognised as a natural resource in most European countries with operational geothermal energy projects.[14] Where existing legal definitions did not include geothermal energy initially, legislation was amended, or new regulation passed that defines geothermal heat as a natural resource. In the Netherlands and Germany, for example, the respective national mining laws were adapted to include geothermal energy, defining clear rules of ownership, regulations, and licensing arrangements.

Medium-term

1. Consideration should be given to identifying **a regulatory body that could take on the effective stewardship and regulation of geothermal energy.** Further stakeholder consultation, including potential regulators, is recommended to identify a suitable regulatory body.
2. To ensure that the potential regulator is provided with the appropriate remit, resources and legal powers, a review of existing legislation is recommended to clarify the status and ownership of geothermal energy. Some changes to the legislative framework may be needed to ensure that **geothermal energy is recognised as a natural resource** that can be licenced, regulated and managed.

[241] Geological Data Act (2020) (in German)

3. As the UK's experience in the development, operation and regulation of geothermal projects grows, it is recommended that consideration is given to **reviewing (and streamlining) existing regulations.** Further engagement with the responsible regulator(s) and stakeholders will be required to investigate if available regulations and processes are suitable for geothermal operations and for supporting timely and effective decision making. Such a **review could include development of regulatory guidelines for deep geothermal energy projects** that can be shared and adopted by industry, local authorities and regulators to ensure that the regulatory processes are understood and applied consistently across the country.

Long-term

4. Consideration should be given **to developing a licensing system for the exploration and operation of deep geothermal projects**. This will become more important as the sector matures and demand on deep geothermal resource increases. In addition to providing security for developers and investors, licensing enables regulators to manage the sustainable use of the UK's deep geothermal resources. Licences should specify ownership and conditions of use, including monitoring and reporting requirements. They could also be used to specify additional conditions, e.g. related to requirements for data sharing (Recommendation 3) or public engagement.

6.4 OTHER CONSIDERATIONS

From the geothermal landscape review and stakeholder engagement, we have identified other measures that are seen as important by different stakeholders for developing a geothermal sector. While responsibility for some of these could be regarded to sit with individual stakeholder groups (e.g. industry), government support could be instrumental in initiating and/or facilitating some of these activities. These measures were not investigated in any detail in this study, and further consideration is necessary to better understand where and how these should be taken forward.

6.4.1 Recommendation 5: Understanding public perception of geothermal energy

There is limited practical knowledge in the UK of public attitudes towards geothermal technologies. While stakeholders consulted in this study perceive public acceptance of geothermal energy as largely positive, other studies suggest that negative perception from other subsurface energy technologies (e.g. shale gas) might have affected the perception of deep geothermal energy (perception spillover) and influenced the conditions that deep geothermal would be expected to meet.[242] While ongoing projects have not met any major opposition, recent planning applications have highlighted public concerns in relation to noise and fear of "industrialising the countryside". Public acceptance will become more important as the sector grows.

The importance of public attitudes has been demonstrated in several countries. In Munich, for example, 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.[243] In Switzerland, lack of public acceptance for geothermal power generation has meant that some cantons and cities have focussed their efforts on geothermal heat production rather than implementing federal objectives for geothermal power generation. As a result, there is still no operational geothermal power project in Switzerland today, despite the availability of strong policy incentives from the federal government.

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[242] Westlake et al. (2023). Perception spillover from fracking onto public perceptions of novel energy technologies. Nature Energy, vol. 8, pp. 149–158.
[243] Abesser, C. & Walker, A. (2022). Geothermal Energy, POSTbrief 46.

Short-term

1. We recommend that a wider consultation with stakeholders, including the public, is considered to gain a **better understanding of public attitudes in relation to geothermal projects**. Such knowledge would inform public consultation procedures and social science approaches to behavioural change. It would benefit the sector as a whole, including developers, operators and regulators, by enabling early dialogue and implementation of actions that address public concerns and enable a positive public experience with geothermal energy. Recent experiences in Northern Ireland (including the #NIGeothermalWeek[13]) provide a positive example of public engagement and building consensus amongst stakeholders across multiple levels to support and steer geothermal policy making. The Department for the Economy, adopted a stakeholder-led approach to developing Northern Ireland's geothermal vision that gave stakeholders the opportunity to engage, explore and articulate the geothermal opportunity and risk issues embedded at different community and project transitioning levels. The approach recognises the important role of the public in the energy transition. It acknowledges findings from previous studies which highlight that one of the most significant challenges is that of building public confidence, shifting attitudes and engaging with public values and perceptions.[244,245]

6.4.2 Recommendation 6: Facilitating communication between stakeholder groups

A few stakeholders have identified the need to form a strategic stakeholder body (or industry task force).[36] This option was not further investigated in our stakeholder engagement as the representation of industry interests and coordination between stakeholder groups is typically led by national trade associations. A range of groups can be identified that have an interest in or promote geothermal energy (including shallow resources, mine energy and thermal energy storage) in the UK (e.g., Table 8). Some groups, i.e. the Net Zero Technology Centre together with the Durham Energy Institute (Durham University) and SHIFT Geothermal, have announced plans to form a Geothermal Innovation Centre. However, the UK approach remains very disjointed, with different interest groups and associations leading separate conversations at local levels of interest and limited connections nationally or across the sector (i.e. between the ground source industry and deep geothermal heat and/or power projects).

Short term

1. UK Government could have a role in **supporting communication between the different stakeholder groups in this sector** and work with the geothermal community (e.g. through consultations and with the existing groups) **to establish an overarching stakeholder/industry body**. Further consultations with stakeholders are needed to better understand what role government could play in facilitating such communication and how it would benefit the sector.

Medium term

2. Consideration could be given to engaging experts from industry, academia and regulators in the **formation of specialist groups that advise government** on decisions relating to building the geothermal energy sector. Such groups could support some of the activities identified in the above recommendations, e.g. the review of regulation (Recommendation 4.3) or supporting the development of a licensing system

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[244] Palmer, M. et al. (2022). Net zero pathways: Building the geothermal energy sector in Northern Ireland. Department for the Economy. Technical Report, pp. 1–136.
[245] United Downs Deep Geothermal Power project. A project exploring public perceptions of geothermal power in Cornwall. University of Plymouth.

(Recommendation 4.4). Northern Ireland’s Department for the Economy, for example, has set up a Geothermal Advisory Group (GAC) to provide independent advice to the Department on the advancement of geothermal technologies in Northern Ireland. In the Republic of Ireland, a new government advisory body, the Geothermal Energy Advisory Group, was formed to advise government on policy and regulation of geothermal energy, including the development of Northern Ireland’s new geothermal bill.

Table 8: Examples of groups and associations with an interest in geothermal energy in the UK.

Key groups involved in promoting geothermal energy in the UK		
Geothermal Task Force (previously the Mine Energy Task Force) [I]	Northern Ireland Geothermal Advisory Committee (GAC) [E]	European Geothermal Energy Council (EGEC) – (A)
Renewable Energy Association (REA) [A]	Energy Group of the Geological Society of London [E]	International Geothermal Association (IGA) [A]
Association for Decentralised Energy (ADE) [A]	Ground Source Heat Pump Association (GSHPA) [A]	International Energy Agency Geothermal Technical Collaboration Programme (IEA Geothermal TCP) [E]
Geothermal Energy Advancement Association (GEAA) [A]	Net Zero Technology Centre (NZTC) [I] SHIFT Geothermal [I]	International Mine Water Expert Group of the IEA Geothermal TCP [E]
General stakeholder groups with interest in the sector		
Policy makers	Regulators	Industry
Consultancy	Academia	Councils/Public sector

E - Expert groups
I - Industry-led interest groups, consortia, or centres
A - membership-based organisations /associations

A summary of our recommendations is provided in Table 9 below based on the short-term (< 5 years), medium-term (5-15 years) and long-term (>15 years) framework in Figure 34.

Table 9: Summary of recommendations for the short-term (< 5 years), medium-term (5-15 years) and long-term (>15 years).

	Short Term	Medium Term	Long Term
1. Reviewing financial support for geothermal energy	Support mechanisms that reflect market maturity		
	Measures to encourage technology uptake (e.g. Feed-in Tariff, Contract for Difference)	Measures for scaling up the deployment (e.g. rolling funds)	Measures to encourage continuous growth until the market is fully matured (e.g. schemes with risk sharing options)
2. Signposting the role of geothermal in UK net zero efforts	Improving visibility of geothermal energy technologies in UK government strategies		Defining long-term targets for the sector
3. Improving data availability and accessibility	Supporting the reviewing, processing and sharing of legacy data	Developing a single geothermal data platform for publicly available data sets and geothermal information	Government supported exploration programmes Introducing data sharing obligations
4. Reviewing the legal status, regulation and licensing of geothermal energy		Identifying a regulatory body Defining geothermal energy as a natural resource Streamlining existing regulations	Licensing system for deep geothermal projects
5. Understanding public attitudes towards geothermal energy	Researching public perception to enable a positive public experience with geothermal energy		
6. Facilitating communication between stakeholder groups	Supporting communication between stakeholder groups to establish overarching stakeholder/industry body	Developing specialist groups that advise government	

Appendix 1 - List of deep geothermal projects and exploratory boreholes in the UK

	Location	Status	Type of geothermal system	Capacity	Description
Southampton Geothermal Heating Company Ltd.	Southampton	Operational for more than three decades, but currently offline.	Hot sedimentary aquifer	1.8 MW_{th}	Borehole from the early 1980s brought into production in 1987 connected to a city centre district heating scheme. It exploited the Sherwood sandstone (depth interval of 1725–1749 m). The brine was extracted at a temperature of 76ºC. The well was reported to be offline due to a technical problem with another component of the district heating and cooling network unrelated to the geothermal system and is not in operation.
Eden Geothermal Energy Project	Eden project, nr St Austell, Cornwall	Operational	Engineered geothermal system	3.45 MW_{th} (predicted)	Operational since June 2023 to provide heat for the Eden Biomes and nursery facilities. In the second phase a second well will be drilled, with a power plant constructed for combined heat and power to supply the biomes, greenhouses and other associated facilities.
New Bath Hotel & Spa	Matlock Bath	Operational	Fractured sedimentary aquifer	~0.2 MW_{th}	Outdoor lido fed from natural hot spring waters (27ºC) from the Carboniferous Limestone
Thermae Spa	Bath	Operational	Fractured sedimentary aquifer	~1 MW_{th}	Utilisation of the natural hot spring waters (46ºC) from the Carboniferous Limestone in a modern-day spa.
Jubilee Pool	Penzance, Cornwall	Operational	Open loop GSHP	0.4 MW_{th}	The pool consists of a partitioned sub-section of a seawater pool that is heated with an open loop ground source heat pump supplied from a 400 m deep borehole at an inlet temperature of 25ºC.
Newcastle Helix (Newcastle Science Central	Newcastle upon Tyne	Under development	Deep closed loop	Research facility	Development of a deep closed loop research borehole using existing an existing borehole (Newcastle Science Central borehole) drilled in

Deep Geothermal)					2011 into the Fell Sandstones to a depth of 1,821 m.
United Downs Deep Geothermal Power project	United Downs, nr Redruth, Cornwall	Under development	Engineered geothermal system	1–3 MW_e, 15 MW_{th} (predicted)	Two deep boreholes into the Cornish granites, the deeper at more than 5 km depth, to provide the first power produced with geothermal energy in the UK. The power plant design is being finalised with start of construction estimated in 2023.
Scunthorpe General Hospital	Scunthorpe	Under development	Deep open-loop GSHP		Sherwood Sandstone Group, first well drilled to depth > 500 m
Third Energy	Kirby Misperton, Ryedale	Under development	Re-use of hydrocarbon wells, coaxial boreholes	2.2 MW_{th}	Geothermal energy centre powered by several existing borehole for new distillery complex and nearby agri-heating and community heating.
Stoke Deep Geothermal Project	Stoke-on-Trent	Planned	Fractured sedimentary aquifer	10 MW_{th} (estimate)	Doublet planned to be drilled to a maximum depth of 3,800 m to exploit permeable fractures at an anticipated water temperature of 95ºC. The heat will supply a district heat network in the Etruria Valley.
Penhallow Deep Geothermal Power Project	Penhallow, Cornwall	Planned	Engineered geothermal system (granite)	5 MW_e, 20 MW_{th} (estimate)	Planning Permission granted in 2022. Similar in construction to United Downs (4500 m depth abstraction and 3000 m depth reinjection).
Manhay Deep Geothermal Power Project	Manhay (Helston), Cornwall	Planned	Engineered geothermal system (granite)	5 MW_e, 20 MW_{th} (estimate)	Planning Permission granted in 2023. Similar in construction to United Downs (4500 m depth abstraction and 3000 m depth reinjection).
Mawla	Mawla, Cornwall	Proposed	Engineered geothermal system (granite)	5 MW_e, 20 MW_{th} (estimate)	In the process of achieving planning permission
Tolvaddon	Tolvaddon, Cornwall	Proposed	Engineered geothermal system (granite)	5 MW_e, 20 MW_{th} (estimate)	In the process of achieving planning permission
Cairngorm Mt	Cairngorm Mountains	Proposed	Cairngorm Granite		Feasibility study to be completed in 2023
Southampton General Hospital	Southampton	Proposed	Hot sedimentary aquifer		Feasibility study ongoing
Royal Preston Hospital	Preston	Proposed			Feasibility study ongoing

Eastbourne District General Hospital	Eastbourne	Proposed	Fractured sedimentary aquifer		Feasibility study ongoing
North Manchester General Hospital	Manchester	Proposed			Feasibility study ongoing
Salisbury District Hospital	Salisbury	Proposed	Hot sedimentary aquifer		Feasibility study ongoing
Banks of River Clyde	Glasgow	Proposed	Unknown		Pre-Feasibility
Guardbridge Integrated HSA and Biomass Heat Network	Guardbridge, St Andrews	Proposed	Hot sedimentary aquifer	0.42 MW_{th} (estimate)	This feasibility study (2016) investigates whether a geothermal district heating system, which accesses Hot Sedimentary Aquifer (HSA) potential underlying a brownfield site at Guardbridge in northeast Fife. Scottish Govt Geothermal Energy Challenge Fund.
New Aberdeen Exhibition Conference Centre	Aberdeen	Proposed	Aberdeen Granite	0.5 MW_{th} peak (estimate)	Feasibility study (2016) for a deep geothermal single well (DGSW) on the site of the new Aberdeen Exhibition and Conference Centre (AECC) near Aberdeen Airport. Scottish Govt Geothermal Energy Challenge Fund.
Hill of Banchory	Hill of Banchory	Proposed	Hill of Fare Pluton (granite)	1.6 MW_{th} (estimate)	Potential for a deep geothermal heat project at Hill of Banchory, Aberdeenshire, believed to have a good geothermal potential. The Hill of Banchory heat network, situated on the northern side of the town, offers a ready-made heat customer. Scottish Govt Geothermal Energy Challenge Fund.
Third Energy	NY Moors	Proposed	Re-use of hydrocarbon wells, coaxial boreholes	0.4 MW_{th}	Heating of leisure/tourism facilities such as eco-lodges, botanical gardens and bike hub.
Third Energy	Great Habton/Little Barugh, Ryedale.	Proposed	Re-use of hydrocarbon wells, coaxial boreholes	2.0 MW_{th}	Community heating project using four existing boreholes within a km of each rural settlement.

Third Energy	Pickering, Ryedale	Proposed	Re-use of hydrocarbon wells, coaxial boreholes	0.3 MW_{th}	Geothermal energy centre powered by two existing boreholes for new leisure and school facilities.
Taffs Well thermal spring	Taffs Well, S Wales	Proposed	Fractured sedimentary aquifer		Taffs Well spring flows at 5 l/s at 21°C. Planning is accepted for development of an open loop scheme with discharge to river to heat a local primary school. BGS Wales raised awareness, with plans being taken forward by NewVision Energy Wales and RCT Council.
The Auckland Project	Bishop Auckland	Proposed	Fractured granite/fractured sedimentary rocks	5MW_{th}	Feasibility study ongoing
North of Scotland Malting Plant	Speyside	Proposed	Hot sedimentary aquifer	2.22 MW_{th} (estimate)	Assessment of geothermal energy potential of the Devonian sandstones extending ~3 km below a whisky distiller's malting facility in the north of Scotland.
Outskirts of Edinburgh	Edinburgh	Proposed	Hot sedimentary aquifer	1.3 MW_{th} (estimate)	A major development plan includes new commercial and residential properties on the western periphery of Edinburgh was reviewed for minewater heating and cooling potential and the Hot Sedimentary Aquifer (HSA) heating potential beneath the existing and proposed development area.
Cheshire Basin	Cheshire	Proposed	Hot sedimentary aquifer	0.68 MW_{th} (estimate)	Two phases. Not enough depth to the Sherwood Sandstone Group across the area of interest. Phase 2 focused on to leisure centres.
Heriot-Watt University Campus	Heriot-Watt University	Proposed	Hot sedimentary aquifer	3.24 MW_{th} (estimate)	The study was carried out within the context of the University's low-carbon heat strategy. This study looked at the benefits of installing a geothermal heat system utilising a hot sedimentary aquifer target of up to 300 m thickness located approximately 1500–2000 m below the site.
Oxford Road DHN	Manchester	Proposed	Fractured sedimentary aquifer	7 MW_{th} (estimate)	Proposal to drill a deep (3 km) doublet into the Carboniferous Limestone to provide heat to a district network.

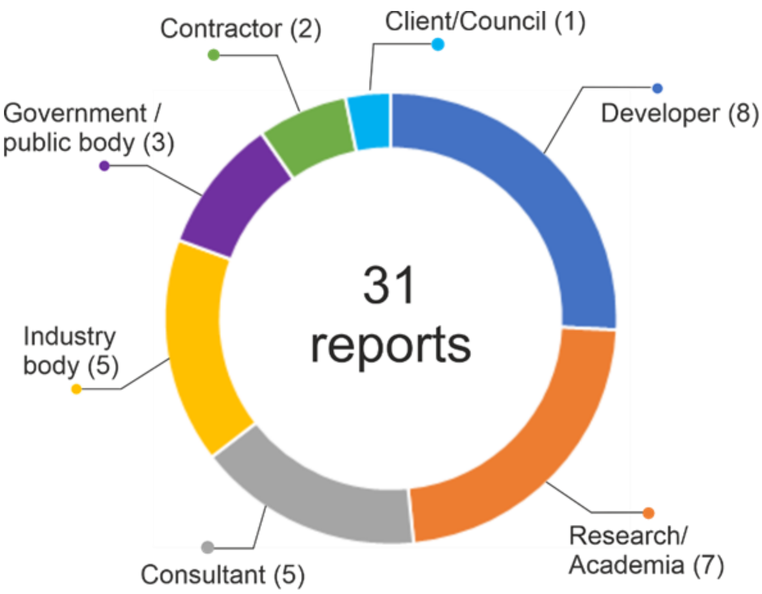
Manchester Metropolitan University, Crewe Campus	Crewe	Proposed	Single borehole heat exchanger	Proposal to drill a 2 km deep single borehole heat exchanger to heat the university campus.
Agricultural College (CAFRE)	Greenmount, Antrim, Northern Ireland	Proposed	Hot sedimentary aquifer	Feasibility study and site investigations to identify a site and plan for a deep test borehole. Commissioned by NI Department for the Economy as part of the geothermal demonstrator project.
Marchwood No. 1	Marchwood	Exploratory borehole	Hot sedimentary aquifer	Drilled in 1980 to a depth of 2609 m. Bottom hole temperature of 88°C. Main aquifer at 1672–1686 m; temperature of the aquifer 74°C.
Cleethorpes No. 1	Cleethorpes	Exploratory borehole	Fractured sedimentary aquifer	Drilled in 1984. Depth 2092. Bottom hole temperature 69°C. Aquifer found at range 1093-1490 m with temperature 44-55°C
Rosemanowes Quarry RH11, RH12, RH15	Penryn, Cornwall	Exploratory boreholes	Granite	Avalon Borehole Test Facility. Previously, the quarry was a UK Hot Dry Rock Geothermal Energy Research site, and the first deep geothermal project, which started in 1977 and concluded in 1991, although studies continued until 1997. Three boreholes up to depths of 2566 m.
Larne No. 2	Larne, Co. Antrim, Northern Ireland	Exploratory borehole	Hot sedimentary aquifer	Completed in July 1981. Part of the UK geothermal exploration programme. Total depth 2873 m, but main aquifer at depth range 960–1247 m. Bottomhole temperature 91°C, but temperatures in the aquifer 40°C.
Eastgate No. 1 and No. 2	Eastgate, County Durham	Exploratory boreholes	Fractured Weardale Granite	Applicability for direct heat uses proved but no economic model for development. Eastgate No. 1 was drilled in 2004. A bottom hole temperature of 46°C was recorded. The main aquifer was at 411 m depth, with an aquifer temperature of 27°C. A second well (Eastgate No. 2) was drilled nearby some years later to a depth of 420 m to evaluate the nature of the fractures in the granite.
Kilroot GT-01	Co. Antrim, Northern Ireland	Exploratory borehole	Hot sedimentary aquifer	Part of a deep geothermal project run by GSNI and funded by the Innovation fund. 2009 Drilled to a

				depth of 868 and fully cored, with a complete section of the Sherwood Sandstone Group.
Silent Valley GT-02	Co. Down, Northern Ireland	Exploratory borehole	Mourne Mountains Complex (granite)	Part of a deep geothermal project run by GSNI and funded by the Innovation fund. Drilled in 2009 to 601 m depth. Granite of the Mournes Mountain Complex. Fully cored and logged.
Ballymacilroy No.1	Co. Antrim, Northern Ireland	Exploratory borehole	Hot Sedimentary Aquifer	Initially drilled in search of coal. It found hot water in the Sherwood Sandstone Group and a geothermal and hydrogeological study was done with logs and temperature profiles

Note: There are other activities, including precursory investigations such as numerical modelling studies, geophysical surveying, and feasibility screening commissions. These are not included in this table.

Appendix 2 - Summary of stakeholder evidence

Table 10: Stakeholder profiles from the different engagements

<table>
<tr>
<td>Analysis of EAC inquiry submissions</td>
<td>(a) 31 submissions


From Arnhardt et al., 2023 (BGS © UKRI 2023).</td>
</tr>
<tr>
<td>Workshop</td>
<td>(b) 34 participants

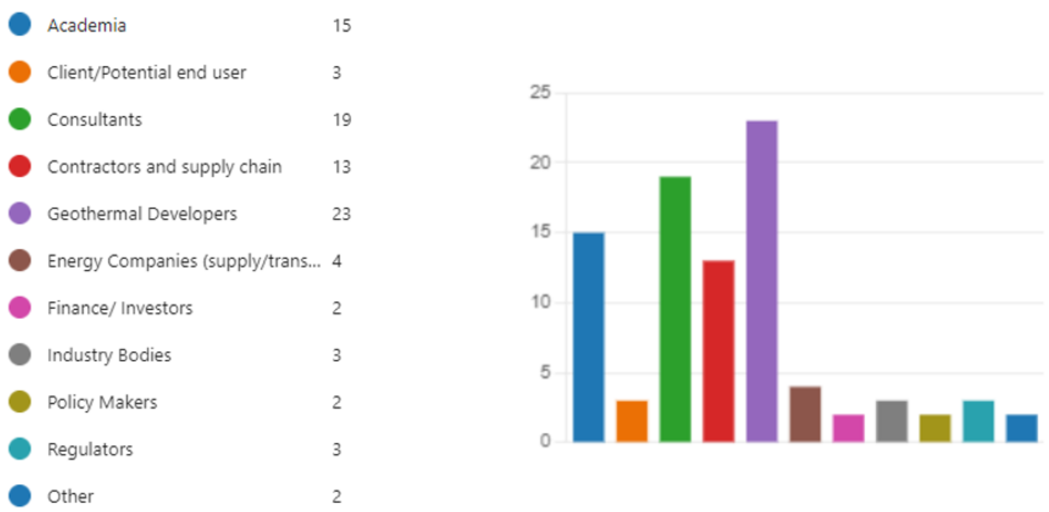
Academia
Clients
Consultants
Contractors
Developers
EnergyCompanies
Finance/Investors
Industry Bodies
Policy Makers
Regulators
</td>
</tr>
<tr>
<td>Online survey</td>
<td>(c) 58 respondents

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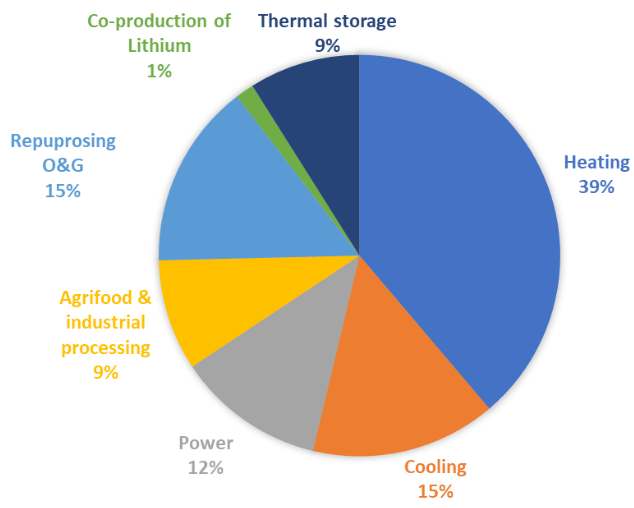
Table 11: Geothermal Opportunities

EAC inquiry submissions

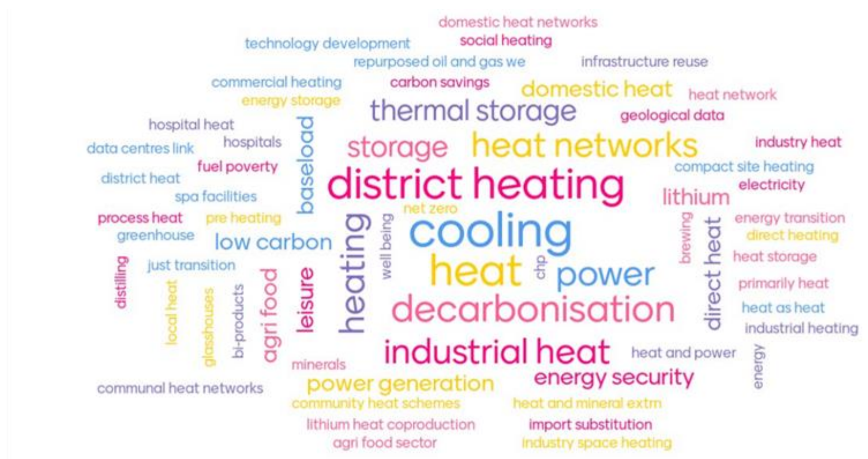
(a)



From Arnhardt et al., 2023 (BGS © UKRI 2023).

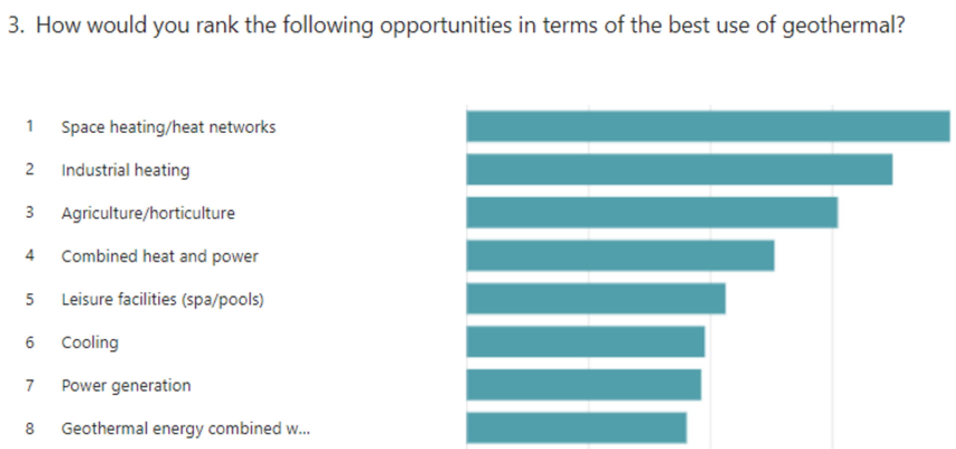
Workshop

(b)

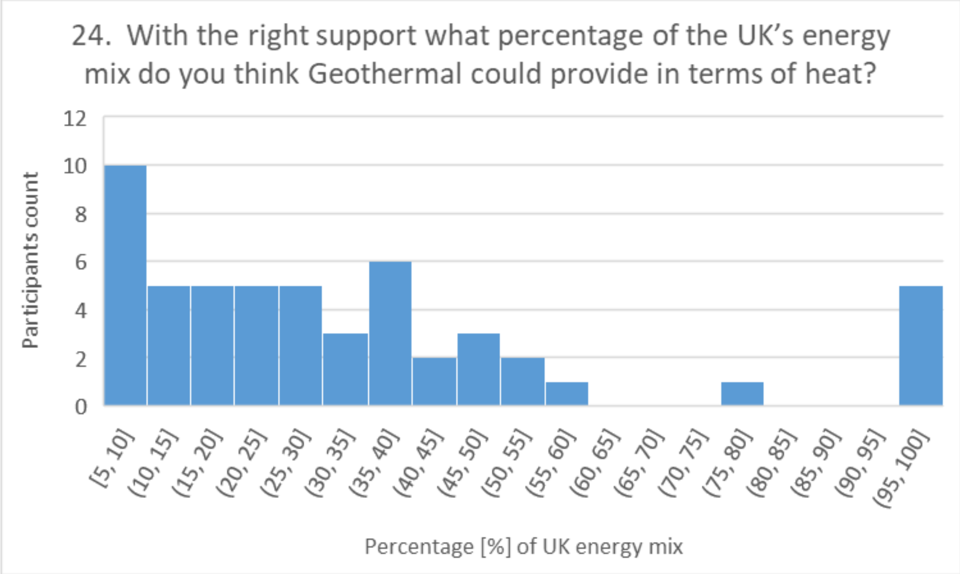


Online survey

(c)

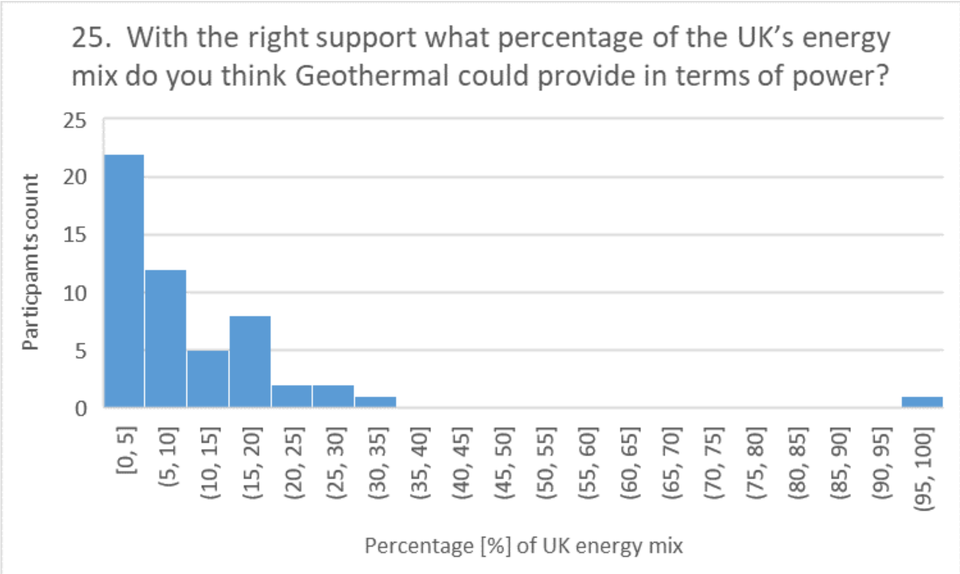


(d)



24. With the right support what percentage of the UK's energy mix do you think Geothermal could provide in terms of heat?
Participants count
12
10
8
6
4
2
0
[5, 10]
(10, 15]
(15, 20]
(20, 25]
(25, 30]
(30, 35]
(35, 40]
(40, 45]
(45, 50]
(50, 55]
(55, 60]
(60, 65]
(65, 70]
(70, 75]
(75, 80]
(80, 85]
(85, 90]
(90, 95]
(95, 100]
Percentage [%] of UK energy mix

(e)



25. With the right support what percentage of the UK's energy mix do you think Geothermal could provide in terms of power?
Particpamts count
25
20
15
10
5
0
[0, 5]
(5, 10]
(10, 15]
(15, 20]
(20, 25]
(25, 30]
(30, 35]
(35, 40]
(40, 45]
(45, 50]
(50, 55]
(55, 60]
(60, 65]
(65, 70]
(70, 75]
(75, 80]
(80, 85]
(85, 90]
(90, 95]
(95, 100]
Percentage [%] of UK energy mix

Table 12: Challenges (© North East LEP except for (a))

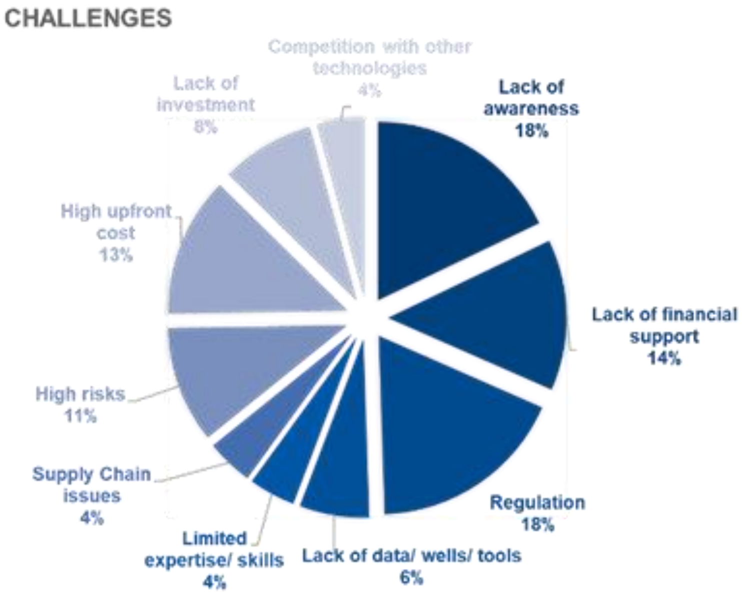
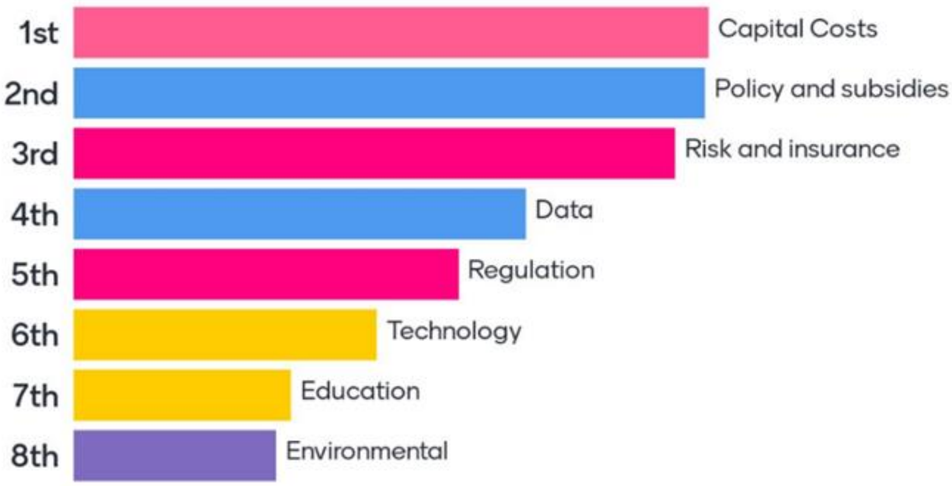
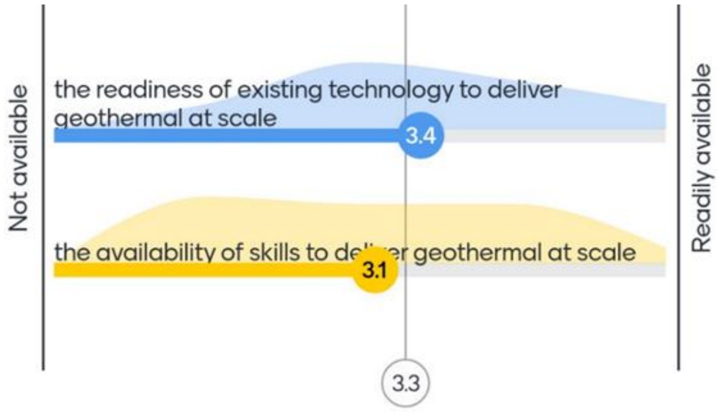
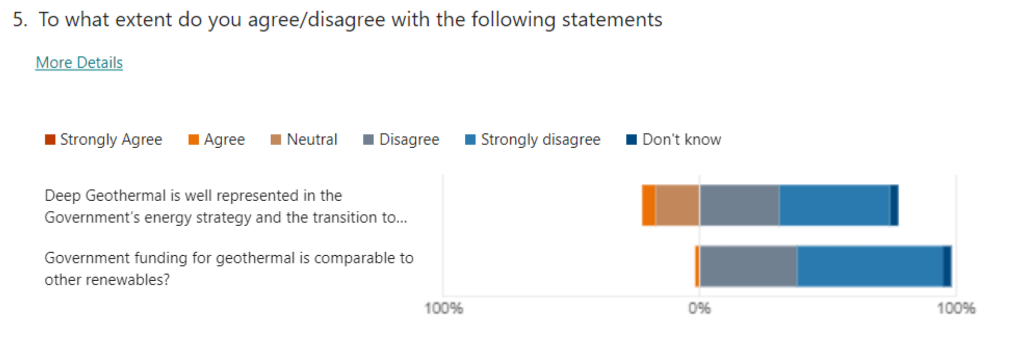
EAC inquiry submissions	(a)  *From Arnhardt et al., 2023 (BGS © UKRI 2023).*
Workshop	(b) 

Table 13: Sector recognition and readiness levels (© North East LEP).

<table>
<tr><td>Workshop</td><td>(a)

Rank the readiness of existing technology and the availability of skills to deliver UK Deep Geothermal at scale (such as community scale rather than existing demonstrator projects).


</td></tr>
<tr><td rowspan="3">Online survey</td><td>(b)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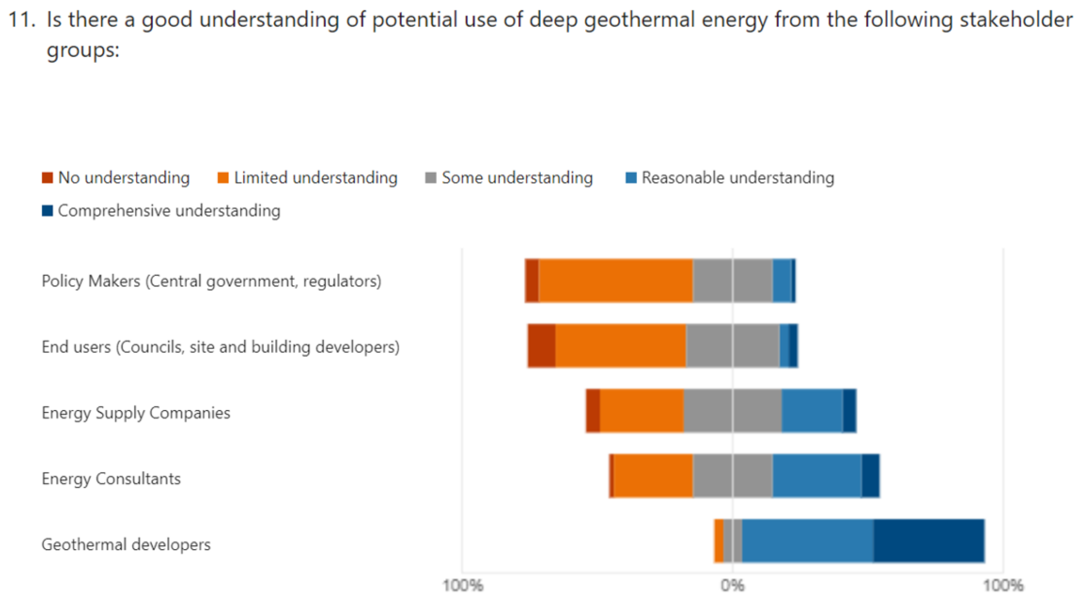
<tr><td>(c)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<tr><td></td></tr>
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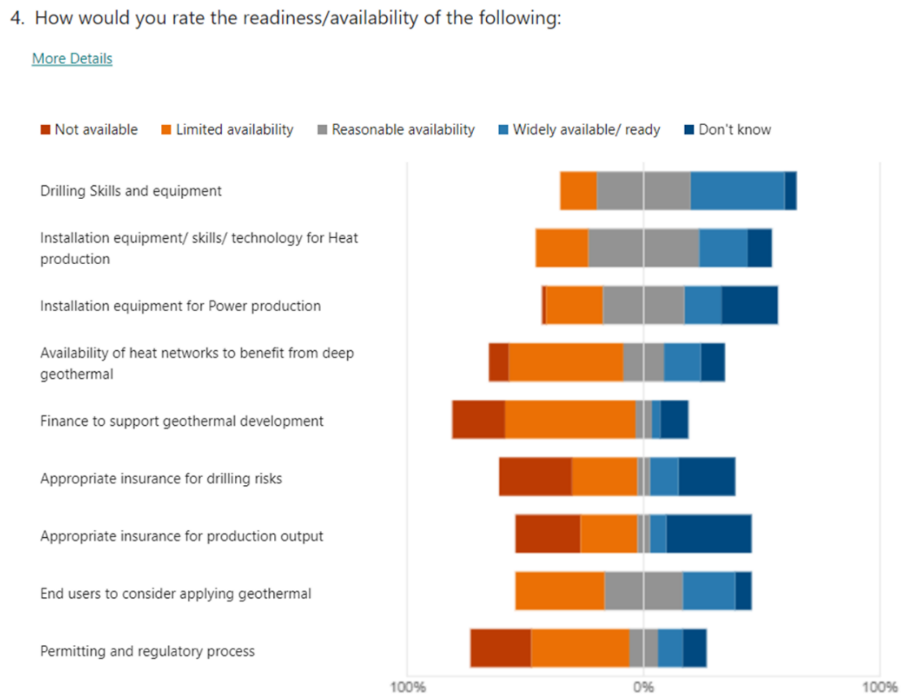
(d)

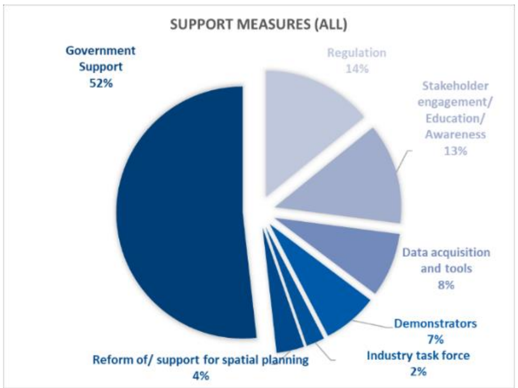


4. How would you rate the readiness/availability of the following:
More Details
Not available
Limited availability
Reasonable availability
Widely available/ ready
Don't know
Drilling Skills and equipment
Installation equipment/ skills/ technology for Heat production
Installation equipment for Power production
Availability of heat networks to benefit from deep geothermal
Finance to support geothermal development
Appropriate insurance for drilling risks
Appropriate insurance for production output
End users to consider applying geothermal
Permitting and regulatory process
100%
0%
100%

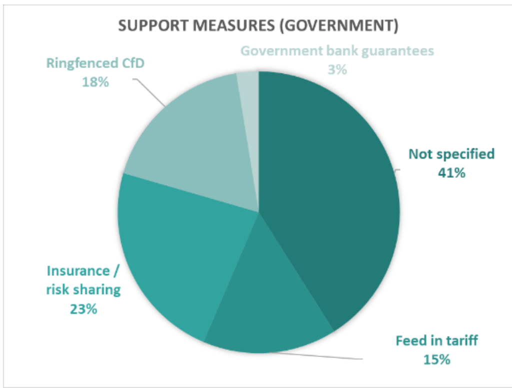
Table 14: Policy framework & support measures (© North East LEP except for (a)).

EAC inquiry submission

(a) Support measures identified by respondents



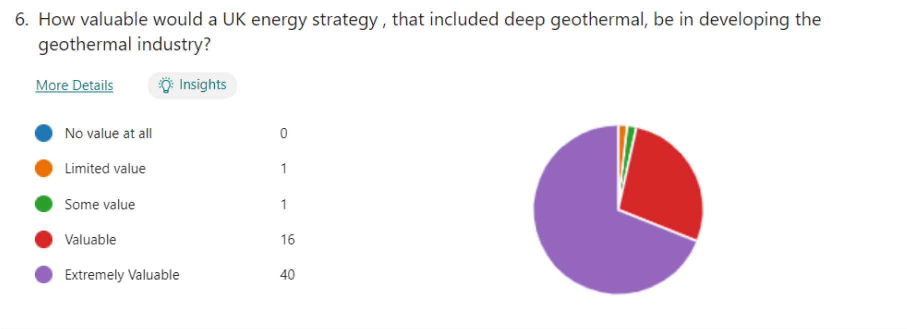
From Arnhardt et al. 2023



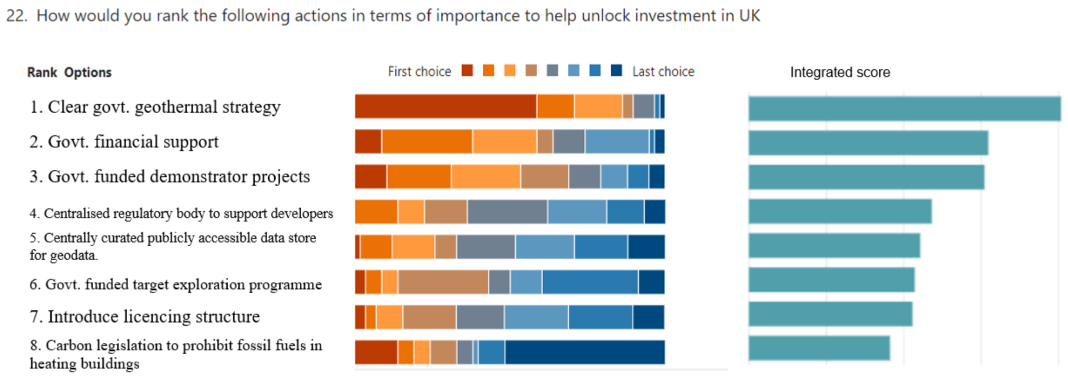
From Arnhardt et al. 2023

Online survey

(b) Recognition of geothermal energy in UK energy strategy

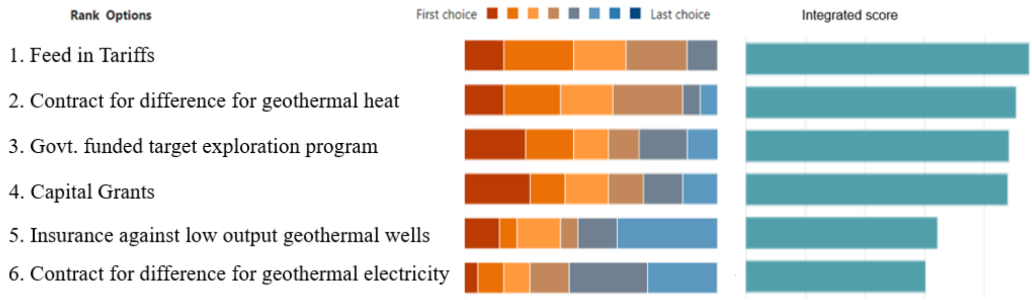


(c) Prioritisation of support measures

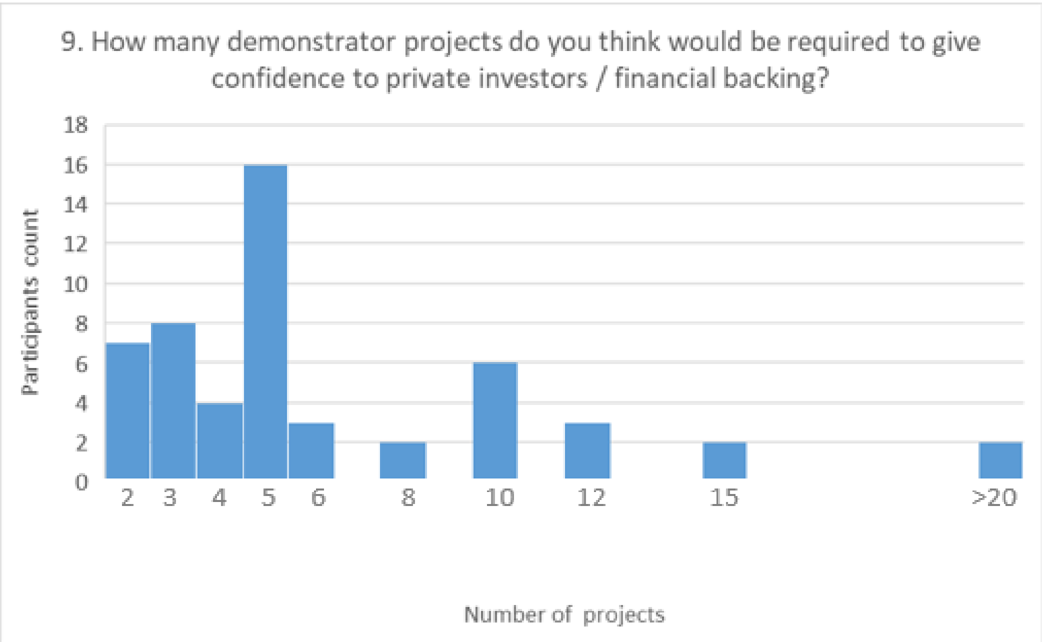


(d) Government financial support measures

23. How would you rank the following **government** financial support (most important/valuable first)



(e) Demonstrator projects



(f) Data sharing obligation

12. Do you think companies should be mandated to share information on deep geology/temperature profiles for others to use? Yes/No

(g) Government investment to build UK geothermal sector

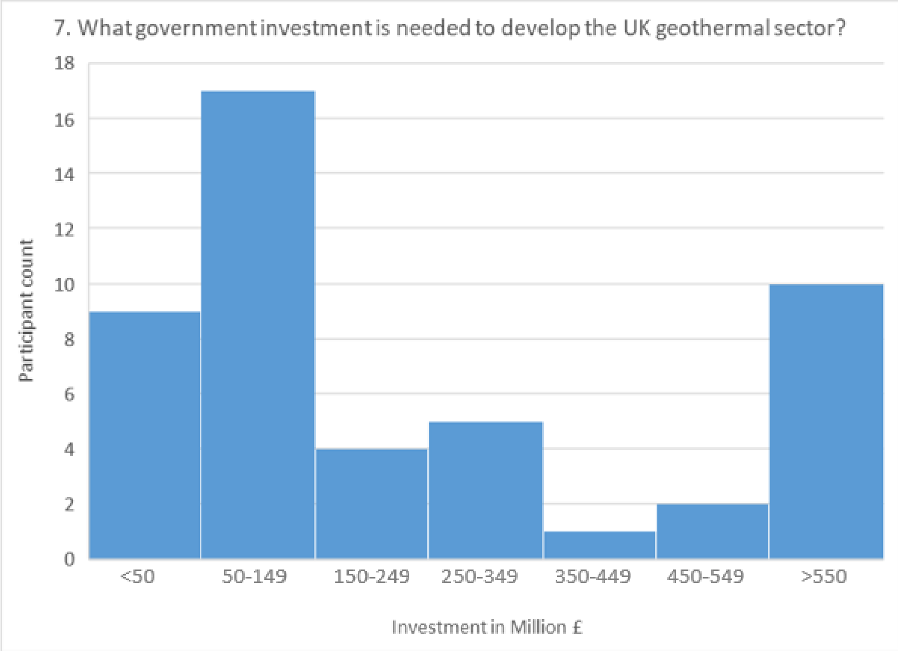
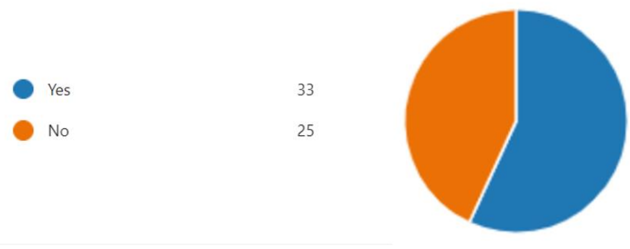


Table 15: Regulation (© North East LEP).

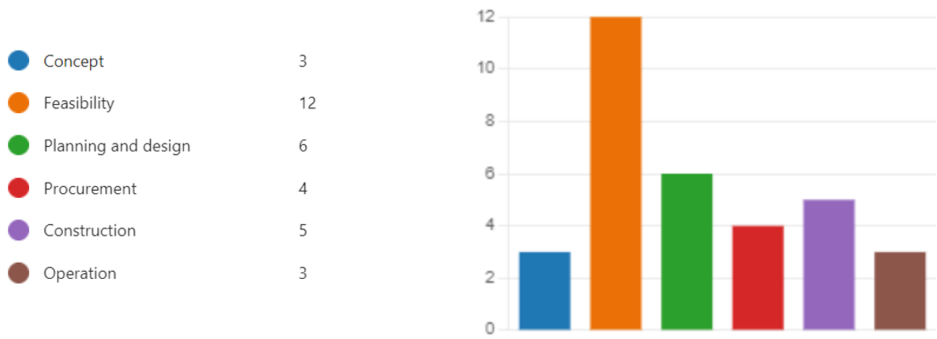
Online survey

(h) Participants' experience – project stage

15. Have you been involved in developing a geothermal project in the UK?

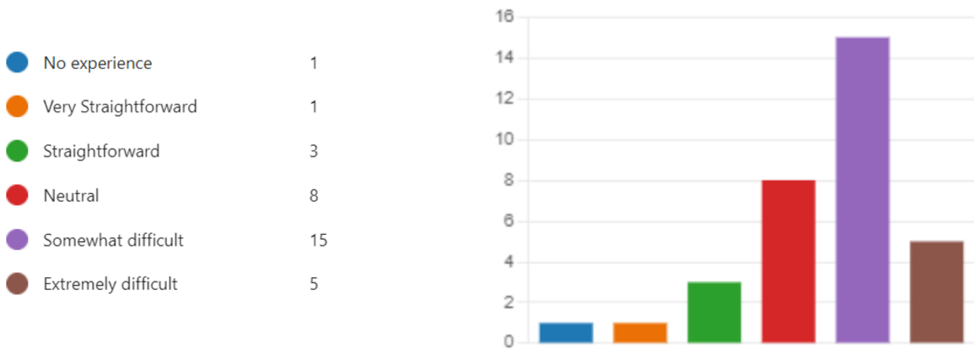


16. At what stage is your project?



(g) Experience with regulatory system

17. How difficult have you found the regulatory requirements for your deep geothermal project?



(h)

19. Would a centralised licensing body be beneficial for geothermal regulation?

(i)

21. Do you consider the regulatory and consenting costs comparable to those for other renewables?

Much more expensive	2
More expensive	17
About the same	11
Cheaper	1
Much cheaper	0
Don't know	27

Table 16: Public perception & acceptance

Online survey

(a)

13. How would you rate public acceptance of geothermal energy in the UK?

Very low	3
Low	15
Average	16
High	18
Very High	6

(b)

14. How important is public engagement in the planning of a geothermal project?

Not important	1
Limited importance	1
Some importance	3
Important	6
Extremely important	47

Appendix 3 – Barriers and policy measures review

Table 17: Key barriers and examples of potential policy measures to address them.

	N[246]	Key barriers	Policy measures	Examples	Comments
Project costs and risks					
	1	High capital costs	Feed-In Tariff	UK Renewable Heat Incentive (RHI)	Tariffs need to be set at right level to encourage uptake
			Capital grants and loans	European Regional Development Fund (ERDF)	Grants have allowed geothermal projects in Cornwall to progress
	2	High exploration and drilling risks	Supporting collection of new data	Dutch SCAN programme	Improving data coverage in priority areas could improve the benefit-risk ratio of geothermal projects
			Risk insurance funds or loans	Risk insurance for drilling and exploitation in France	Feasibility depends on market maturity and competing budget requirements
Technology awareness					
	3 + 11	Geothermal not represented in Government policy documents and renewable targets	Roadmap and action plans that set out milestones and targets for geothermal heating	Master Plan Geothermal Energy - Netherlands	Targets need to be backed by market incentives
			Geothermal Task Force or Association	Stichting Platform Geothermie - Netherlands	Platform for stakeholders from industry, research and government to work together in supporting development of the geothermal sector
	4	Lack of technology recognition and awareness and/or public acceptance	Public campaigns	Public campaigns on geothermal energy in the United States (GRC, 2020)[247]	Campaigns can be more effective when they showcase the results of successful demonstration projects
Government support & investment					
	5 + 9	Lack of financial support mechanisms	As No. 1		
	6	Difficulties with assessing the available funding mechanisms for the public sector decarbonisation	Review of funding mechanism		Extending length of grants and time scale over which carbon saving are expected would enable geothermal to benefit
	7	Portfolio approach is	Funds or loans that enable		Rolling funds/ loans have been suggested

[246] This refers to barriers identified in chapter 7.
[247] GRC (Geothermal Resources Council) (2020), "Geothermal energy's dynamic potential as a clean source of renewable energy to be showcased in public relations campaign", Geothermal Resources Council, www.geothermal.org/PDFs/News_Releases/2020/February_7-Geothermal_Marketing_Campaign.pdf.

		needed to decarbonise the public sector estate	multiple projects to progress simultaneously		
	8	Geothermal power projects unsuccessful in winning Contracts for Difference	Ringfenced pot for geothermal power generation	£20 million ring-fenced CfD funding for Tidal stream projects[248]	Ring-fenced CfD funding enables projects in nascent sectors to secure investment, scale up and reduce costs
	10	Lack of legislative support relating to low-carbon heating	Phase out date for fossil fuel heating	UK car industry ban on fossil fuel cars	Needs market incentives and skills support to enable transition to low-carbon heating
			Carbon taxation or extension of UK ETS[249] to buildings sector	2013 UK carbon price floor[250]	This could help to reduce the competitive advantage currently held by high-carbon options[251]
Data availability & accessibility	12	Limited data availability and accessibility	Data collection and sharing	Geotis (Germany), ThermoGIS (NL)	Synergies with other energy sector (CCS, Energy storage, O&G) could be beneficial
			Data sharing obligations	German Geological Date Law	Data sharing obligations could be linked to subsidies / licensing conditions
UK geothermal supply chain & Technology	13 - 18	Supply chain disengaged and/or not coordinated	Long-term commitment to & policy support for geothermal – as No. 3	Master Plan Geothermal Energy - Netherlands	Robust and credible long-term planning will provide investment security and market confidence
			Support measures to build pipeline of projects – as No. 1	RHI, EDRF	Project pipeline needed to re-engage supply chain and encourage transitioning from O&G sector
			Government funded and private demonstrators	Northern Ireland deep geothermal demonstrator	Demonstration projects entail uncertainty but demonstrate technology and business case to supply chain
			Industry clusters for heating and/or cooling or district heating technologies	Danish District Heating market	Cooperation and knowledge exchange between industry and research helps supply chains to test technologies and operational models
		High drilling costs	Support for Research & Innovation	Rijswijk Center for Sustainable Geo-energy in the Netherlands[252]	Faster and deeper drilling is key for reducing costs and scaling up the industry
	20	Uncertainty in the status,	Legal definition of geothermal	Mining Act, Netherlands	This is a prerequisite for regulation and licensing of heat.

[248] Energy Voice (2021) UK Government announces £20m ring-fenced tidal funding in upcoming CfD.
[249] https://www.gov.uk/government/publications/participating-in-the-uk-ets/participating-in-the-uk-ets
[250] New York Times (2019)
[251] London School of Economics & Energy Systems Catapult (2022). The future of UK carbon policy: how could the UK Emissions Trading Scheme evolve to help achieve net-zero? Policy Paper.
[252] ThinkGeoEnergy (2020). Working on drilling technology for geothermal in Rijswijk, Netherlands

Regulation		ownership, and regulation of geothermal energy	energy as a natural resource		
			Licensing regime for geothermal	Netherlands, France and Germany	Licensing is needed to attract investors. Requires critical mass of projects to inform the process.
	21	Inconsistencies in regulation	Regulating authority with remit for geothermal	Netherlands and Badem Würtemberg (Germany)	Central regulator or coordinating body will ensure consistency and faster development of regulatory expertise.
			Bespoke and streamlined regulation and permitting process	France, Netherlands and Germany	Unclear regulation can have impact on public confidence. Complex permitting process reduces willingness for industry to engage.

Appendix 4 - Geothermal development road map

The following road map is developed from international experience in developing deep geothermal targets, typically using conventional doublet systems (consisting of two or more wells). Due to limited development of the industry in the United Kingdom, domestic experience currently relates to individual pilot projects and is thus atypical of that in a well-developed sector. For example, in many pilot projects, as seen in the UK currently, the exploratory and test drilling phase tends to be curtailed for cost-saving reasons. Where possible, UK specific information is provided in this road map. However, as the deep geothermal industry in the UK has few examples, formal routes for planning and consenting projects are not yet in place, and there is currently no geothermal licensing system. The road map should therefore be considered in the context of this nascent industry and updated as more experience is gained, and more formal processes are introduced.

The development phases have been divided into the following phases:

Pre-feasibility: At pre-feasibility stage the project concept is being defined: Is there a suitable source of geothermal energy, is there a user demand, would a project be likely to gain consent and be funded? This phase comprises desk-based studies investigating geological data from national sources, such as the BGS, or published literature (temperature gradients, geological stratigraphy and structure, geochemical data) to identify locations and depths of potential geothermal sources. Demand assessments would also be undertaken to identify how any heat derived from a geothermal project would be used and/or power generated could be connected to the grid or end users. This stage would also include identification of any environmental constraints which could affect the project consenting such as highly sensitive environmental receptors and the route required to obtain permission for the development of the projects including consents required for the exploratory phase of the project. It would also include the financial modelling of the project, identifying how the early stages of the project will be financed, establishing what public financial support is available, and the information needed to leverage this and how the capital cost of drilling and construction of power plants and heat networks will be funded. Other potential programme constraints such as potential lead-in times for equipment availability and grid connections should also be established at this time.

Milestone 1: At the end of the pre-feasibility, the decision is taken whether there is a credible geothermal project that could be financially viable and whether investment in the next investigation stage is feasible.

Milestone 2: Financial model is established and financial backing is set up at this stage.

Feasibility: The project now moves into the phase of confirming the geothermal potential in the ground. Permission must be sought for investigation and exploratory drilling. Projects may seek permission for production drilling at this stage, e.g. where exploratory drilling is not undertaken. Consenting for UK projects to date has been led by Local Planning Authorities (LPAs) using the planning process. Depending on the size of the scheme, Environmental Impact Assessments may be required. In addition to a scheme design for the development, a range of supporting studies will be required to support planning applications such as impact assessments for noise, landscape and visual, water resources, ground and hydrogeology, seismicity, biodiversity and ecology. Consultation with the Environmental regulator (Environment Agency, Scottish Environment Protection Agency, National Resources Wales, Northern Ireland Environment Agency) must be sought to identify what environmental consents or licences (groundwater investigation, groundwater pumping / discharge, NORM) are needed for the project. Public engagement is a key part of the project process and should be planned and implemented as early as possible. Consenting for the drilling works may also be required, for example from the Coal Authority, where drilling through Coal Measures strata in Great Britain. Notice will also need to be provided to the Health and Safety Executive under the Borehole Site and Operations Regulations 1995, prior to any intrusive drilling works. The exploration phase can include a range of techniques from geophysical investigations, mapping structural geology, geochemical testing to investigating the chemical signature of groundwater which gives an estimation of temperature, or the drilling of exploratory boreholes, typically small diameter holes (slim holes) to depths of less than 500 m to investigate the shallow temperature gradient. Test drilling can be undertaken, e.g. by re-entering slim holes to drill to target depth. This provides greater confirmation of likely well output and may comprise several holes for large power projects. A further phase of deeper test drilling may then be undertaken. For recent UK pilot projects, this scale of exploration has not been undertaken. After exploration is complete, the findings of the pre-feasibility study are reviewed and a more refined estimate of the reservoir potential and the geothermal productivity, coupled with risk modelling, is made. The financial viability is then reviewed. The production potential then enables more formal demand modelling combined with risk management - this then dictates the project size, number of wells, and the feasibility for generating power and/or heat. Relevant permits for the next development stage (e.g. production drilling) need to be sought (if not already applied for previously).

Milestone 3: Planning approval, environmental consents and licences.

Milestone 4: Energy supply agreements (ESA) and power purchase agreements (PPA) put in place.

Detailed Design: Completion of the feasibility stage enables the scope and scale of the geothermal project to be confirmed. The findings from the desk-based and exploratory phases and the assessment of the geothermal resource from the reservoir modelling are used to size the production plant and the capacity for heat and/or power production. At this point, ESA and PPA can be put in place with heat customers (e.g. heat network operators, distribution companies). The design of the field development wells in and above-ground infrastructure, e.g. a heat network, heat exchangers or geothermal power plant with grid connection, is then progressed. Design information should include the necessary technical specifications to enable the drilling and construction works to be tendered. It is important to define the ownership of project-related construction risks at the tender stage. This additional detail enables the capital costs to be refined.

Milestone 5: Contract Tender.

Procurement: Drilling and construction works are procured, and lead-in times to construction commencement can be defined based on availability of drilling equipment and materials. At this stage it is important to ensure that all relevant permissions and permits are in place, including specific working requirements, plant and method statements from the contractors.

Milestone 6: Contract award

Construction, testing and commissioning: Drilling for the production and (where required), injection wells is undertaken. On completion of drilling and well construction, each well is tested, and production testing and monitoring is undertaken. The results are, again, used to refine estimates of production potential and update commercial predictions. Monitoring of the drilling and construction process is put in place at the start of this stage to ensure compliance with conditions imposed during planning approval, including monitoring of micro-seismicity during well drilling and testing. Following well completion and testing, construction of above-ground infrastructure is completed and production commences.

Milestone 7: Production Commences

Operation: Production output is continually measured and monitored to ensure optimal performance of the well and pumping system. During operation, allowance is needed for regular maintenance of the well system and production plant to ensure productivity and longevity of the well is not impacted.

Decommissioning: At the end of the production phase, allowance should be made for either the repurposing of the well or the decommissioning of the well. This involves removing of the head works, backfilling and sealing of the well to avoid any long-term environmental impacts that the well may have by creating pathways for groundwater, ground gas or potential contamination, in addition to the reinstatement of the above ground works.

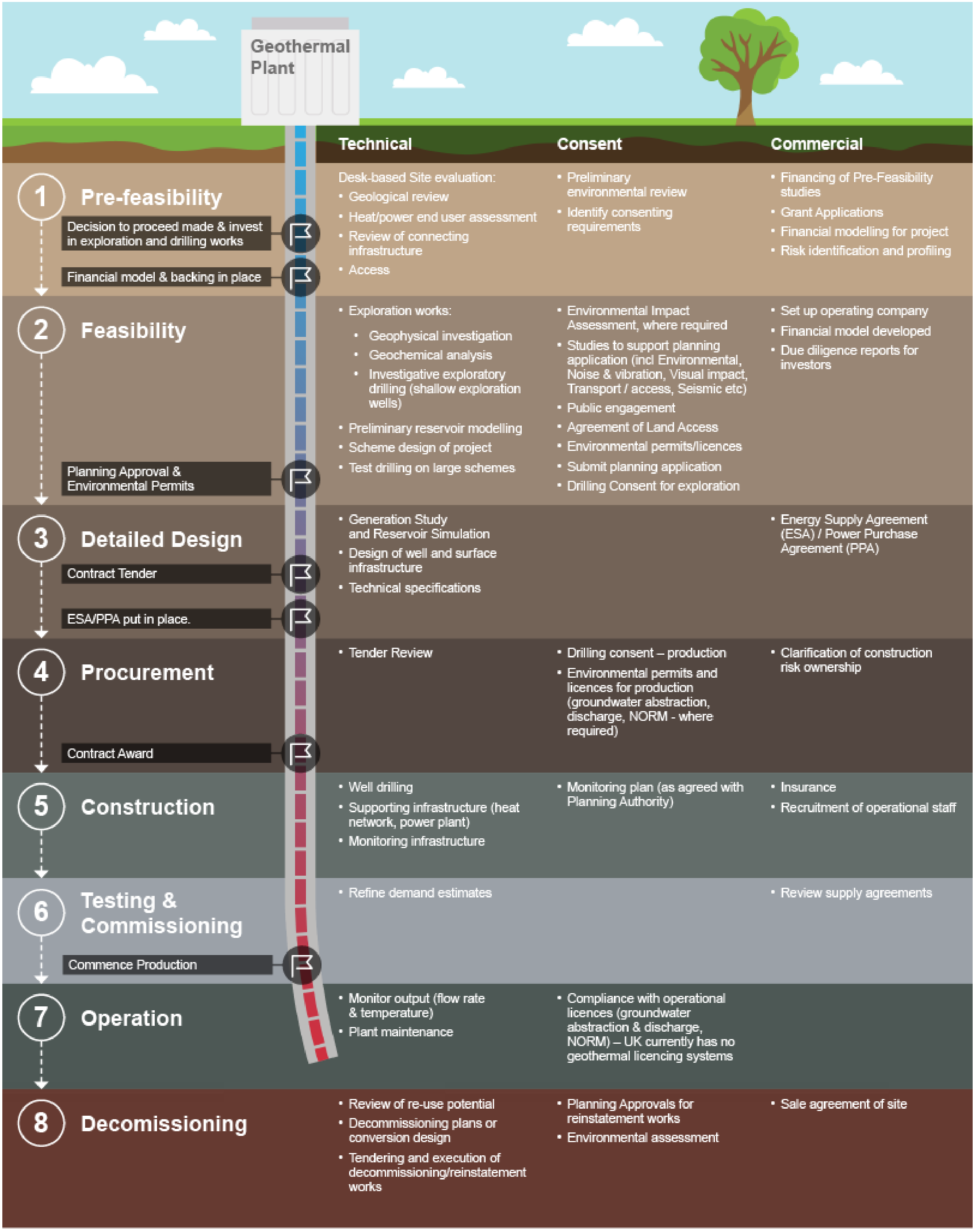


Figure 37: Roadmap for development of a deep geothermal project in the UK (© North East LEP).

Table 18: Tabulated presentation (including time scales) of the key stages of project development shown in Figure 37.

Stage	Timescale	Technical	Consent	Commercial
Pre-feasibility	0.5–1 years	Assessment of site location and evaluation comprising desk-based assessments: - Geological review, - End-User demand, - drilling access, - heat/grid connection or receptor	Preliminary environmental review Identify consenting requirements	Financing of Pre-Feasibility studies Grant Applications Financial modelling for project Risk identification, modelling and pricing/insuring
Milestone 1:	Decision to proceed made and invest in exploration and drilling works			
Milestone 2:	Financial model and backing in place			
Feasibility	2 years	Exploration works: - Geophysical investigation - Geochemical analysis - Investigative exploratory drilling (shallow exploration wells) Preliminary reservoir modelling Scheme design of project Test Drilling	EIA, where required dependent on project size and location. Studies to support planning application: - Environmental assessment - Noise impact - Visual Impact - Transport etc Public engagement Land ownership Planning Application Drilling consent – exploration Environmental permits and licences (groundwater abstraction, discharge, NORM) (where required)– exploration	Set up operating company Financial model developed Due diligence reports for investors
Milestone 3:	Planning Approval and Environmental Permits			
Milestone 4:	ESA/PPA put in place.			
Detailed Design		Generation Study and Reservoir Simulation Well design and surface infrastructure Technical specifications		Energy Supply Agreement/Power Purchase Agreements
Milestone 5:	Contract Tender			
Procurement		Tender review	Drilling consent – production Environmental permits and licences (groundwater abstraction, discharge, NORM) (where required) - production (where required)	Clarification of construction risk ownership
Milestone 6:	Contract award			
Construction	3–6 months	Well drilling	Monitoring plan (as agreed with Planning Authority)	Insurance Recruitment of operational staff

	1–2 years	Supporting infrastructure (heat network, power plant) Monitoring infrastructure		
Testing and commissioning		Refine demand estimates		Review supply agreements
Milestone 7:	Production Commences			
Operation		Monitor output (flow rate & temperature) Plant maintenance	Compliance with operational licences (groundwater abstraction & discharge, NORM) – UK currently has no geothermal licensing systems	
Decommissioning		Review of re-use potential Decommissioning plans or conversion design Tendering and execution of decommissioning/reinstatement works	Planning Approvals for reinstatement works Environmental assessment	Sale agreement of site

Appendix 5 - Conversion of heat in place to recoverable heat energy

HEAT IN PLACE (HIP)

The calculations of geothermal potential or "Heat in place" presented in this paper are given as PJ/km^2. These values quantify an estimate of **all heat that is stored in the geothermal reservoir** within a 1,000m x 1,000m area.

Heat in place estimates in this paper were calculated using the 3DHIP-Calculator developed by the Cartographic and Geological Institute of Catalonia[253] and described in Piris et al. (2020).[254] 3DHIP computes the volumetric heat in place (HIP in PJ/km^2) using the most recent reformulation by the USGS[255] which is an update from the classical formulation from Muffler and Cataldi (1978) expressed as:

$$HIP = V\,[\varphi \cdot \rho_F \cdot C_F + (1 - \varphi) \cdot \rho_R \cdot C_R](T_R - T_S) \qquad (1)$$

with φ = porosity of the reservoir rock; ρ_R and ρ_F = density of the rock and the fluid, C_R and C_F = specific heat capacity of the rock and fluid, and T_R and T_S = the reservoir temperature and surface temperature, respectively.

Traditionally, T_S is assumed to be the surface ambient temperature, but Carg and Combs (2015)[255] recommend to use the abandonment temperature as it will provide more realistic (less optimistic) results. In this work, as in Jones et al. (2023),[256] a value of 21°C was used for the calculation.

RECOVERABLE HEAT (H_{REC})

Recoverable heat is the **proportion of the available heat that can be economically recovered** from the subsurface. It is therefore a subset of the heat in place.

The estimation of the recoverable heat is more complex as it requires knowledge of (or assumptions relating to) aquifer properties (such as flow rates, effective porosity, aquifer thickness), as well as plant and operational parameters.

The equation for estimating the recoverable heat (H_{REC} in kW or MW) in 3DHIP uses the following input parameters: heat in place (*HIP*), the conversion efficiency of the heat exchanger (C_e), a recovery factor (*R*), the expected lifetime of the project (T_{live}) and proportion of time the plant is expected to be operating (plant factor, P_f).[257]

$$H_{REC} = \frac{HIP \cdot C_e \cdot R}{T_{live} \cdot P_f} \qquad (2)$$

The recovery factor *R* is estimated from aquifer- and pumping-related parameters.

[253] https://www.icgc.cat/en/Public-Administration-and-Enterprises/Services/Geothermics/Deep-Geothermal-Potential-Assessment-3DHIP-Calculator
[254] Piris, G.; Herms, I.; Griera, A.; Gómez-Rivas, E.; Colomer, M. (2020): 3DHIP-Calculator (v1.1) [Software]. Institut Cartogràfic i Geològic de Catalunya, Universitat Autònoma de Barcelona. CC-BY 4.0.
[255] Garg, S. K.; Combs, J. (2015): A reformulation of USGS volumetric "Heat In Place" resource estimation method. Geothermics, 55, 150–158. https://doi.org/10.1016/j.geothermics.2015.02.004.
[256] Jones, D. J., Randles, T., Kearsey, T., Pharaoh, T. C., & Newell, A. (2023). Deep geothermal resource assessment of early carboniferous limestones for Central and Southern Great Britain. Geothermics, 109, 102649.
[257] Piris, G., Herms, I., Griera, A., Colomer, M., Arnó, G., & Gomez-Rivas, E. (2021). 3DHIP-Calculator—A New Tool to Stochastically Assess Deep Geothermal Potential Using the Heat-In-Place Method from Voxel-Based 3D Geological Models. Energies, 14(21), 7338.

EXAMPLE OF HIP TO H_{REC} CONVERSION FOR FIGURES 12-15 OF THE REPORT

Using equation 2 above and parameter values from Table 2 in Jones et al. (2023),[256] a value of recoverable heat can be obtained for the calculated HIP using

$$H_{REC}\,[W/km^2] = \frac{HIP[\frac{J}{km^2}]\cdot 0.85\,[-]\cdot 0.1[-]}{946{,}080{,}000\,[s]\cdot 0.95[-]} \qquad (3)$$

For simplification, the conversion factor for the reference values is approximated as

$$H_{REC}[kW/km^2] \approx HIP\,[\frac{\mathrm{PJ}}{km^2}]\ \times 95 \qquad (4)$$

Using the conversion above, **1 PJ/km^2 heat in place is then equal to ~ 95 kW heat recoverable**.

So, areas in Figures 12-15 where heat in place is estimated as 100 PJ/km^2 may provide approximately 9.5 MW recoverable heat per km^2.

This conversion provides only a rough approximation.

Considering the actual geothermal footprint of the geothermal well (estimated from operational data) provides an estimate of recoverable heat per geothermal well. Assuming a radius of influence of 0.5 km^2 (see Piris et al., 2021)[257] gives the following equivalence

$$H_{REC}[kW] \approx HIP\,[\frac{\mathrm{PJ}}{km^2}]\ \times 75 \qquad (5)$$

Therefore, for a heat in place estimate of 100 PJ/km^{2,} the recoverable heat energy at well head is estimated to be 7500 kW or 7.5 MW.

Conversions for different heat in place values (based on the stated assumptions) are provided in Table 19.

Table 19: Indicative conversion of heat in place estimates to recoverable heat per km^2 and recoverable heat at well head using approximate, uncertain input values and assumptions from Jones et al., 2023 and Piris et al., 2021

Heat in place estimate (PJ/km^2)	Recoverable Heat (per km^2) (MW)	Recoverable heat at the well head (assuming r = 0.5 km^2) (MW)
1	0.1	<0.1
50	5	4
100	10	8
150	14	11
200	19	15
250	24	19
300	29	23
350	33	26
400	38	30

Abbreviations

AGS	Advanced Geothermal Systems
CAPEX	Capital Expenditure
DGE	Deep geothermal energy
DEVEX	Development expenditure
EGS	Enhanced Geothermal Systems
GSHP	Ground Source Heat Pump
OPEX	Operational Expenditure
SHR	Superhot rock systems

Glossary

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, either vertically or inclined, often to locate water or oil.

CAPEX (capital expenditure): This is the major spending required to drill and complete wells for long term use.

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 mean system that produce heat in the 50–200˚C range of medium temperature (steam or water). This may be regarded as medium-high grade heat, suitable for multiple uses including direct use for space heating, industrial and horticulture use 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.

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).

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.

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.

LCOE

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.

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).

OPEX (operational expenditure): the cost required to keep a geothermal plant operational, including ongoing maintenance costs.

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.

Resource (according to UNFC-19)[258]: the cumulative quantities of geothermal energy that will be extracted from the available geothermal energy source. The term is only applicable to areas where the existence of a significant recoverable geothermal energy has been proven (i.e. Known Geothermal Sources).

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.

Technical potential (Beardsmore protocol[259]): the fraction of the physically accessible potential (see theoretical potential) that can be used under the existing technical, structural and ecological restrictions as well as legal and regulatory allowances.

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.

Theoretical potential (Beardsmore protocol): the theoretically realizable energy supply considering only physical constraints (i.e. the physically-usable energy supply) (for comparison see technical potential)

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.

[258] UNECE (2019) Supplementary Specifications for the application of the United Nations Framework Classification for Resources (Update 2019) to Geothermal Energy Resource

[259] Beardsmore GR, Rybach L, Blackwell D, Baron C. (2010) A protocol for estimating and mapping global EGS potential. GRC Trans., 34, pp 301–312.