Northern Ireland Department for Economy

Research into the Geothermal Energy Sector in Northern Ireland

Geothermal Technology and Policy Review

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This report takes into account the particular instructions and requirements of our client. It is not intended for and should not be relied upon by any third party and no responsibility is undertaken to any third party.

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Executive Summary

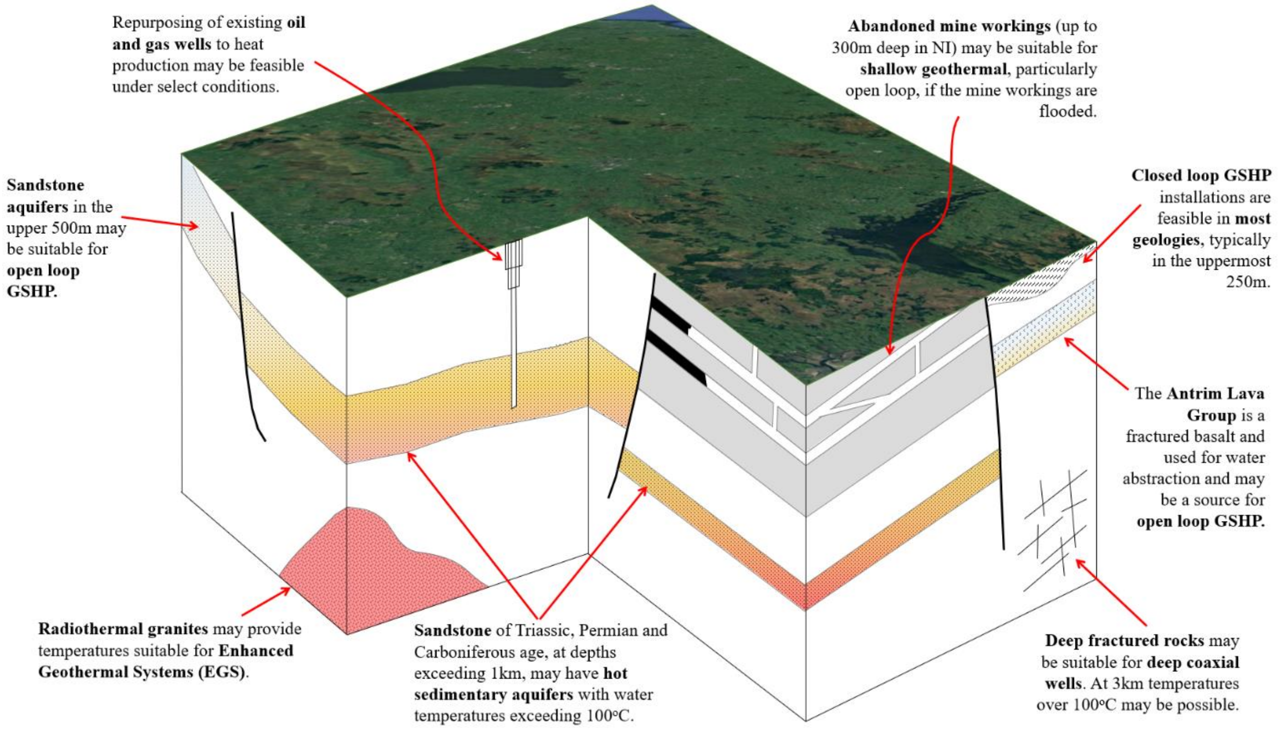
Overview

Arup and the British Geological Survey (BGS) have been commissioned by the Department for the Economy (DfE) to evaluate the current geothermal energy sector in Northern Ireland (NI). This report summarises the work undertaken, including suggestions for changes to policy and regulation which may unlock Northern Ireland's geothermal resource in the future.

The Energy Strategy for NI [1] recognises that geothermal energy can contribute to the decarbonisation of heating and/or cooling. Heating is a critical component to meet these decarbonisation targets given that currently 68% of homes in NI are heated by carbon emitting oil boilers.

Recent analysis of geological data across Northern Ireland by the Geological Survey of Northern Ireland (GSNI) has identified areas with potential for deep geothermal heating projects, particularly around Antrim and in other areas of deeply buried sediment. In combination with shallow geothermal projects, which have applicability more widely, there is no shortage of options for geothermal development in NI. Demand for heat is equally as important as supply for geothermal projects and there are many industries that could benefit from direct use of geothermal heat, and if feasible, geothermal power (noting that the latter requires very specific geological conditions).

Closed loop geothermal systems are generally suitable at any location (subject to land availability for shallow systems), regardless of the geology. In contrast, open loop systems require aquifers (rock units) from which groundwater can be abstracted for heating/cooling, then returned via boreholes or wells. A schematic conceptual geothermal model illustrating the key geological features found in Northern Ireland and the main geothermal technologies suitable is presented in the figure below. Further detail for all shallow and deep geothermal technologies reviewed for this study is presented in Section 4.



High level conceptualisation showing some of the key geological features of Northern Ireland that are applicable to shallow and deep geothermal technologies.

Recommendations

The policy and regulations relevant to geothermal projects in Belgium, Denmark, France, Germany, The Netherlands and Switzerland suggests the following interventions can encourage geothermal projects:

- **Shallow geothermal**: Grant payments for shallow geothermal systems to reduce high upfront capital costs.
- **Deep geothermal**:
  - Government backed loans, grants, or feed in tariffs that incentivise deep geothermal project development.
  - Investment in geological research that can help identify possible project sites.
  - Development of a clear legislative framework specifically for deep geothermal projects.
  - Decisiveness in relation to the licencing of geothermal resource.

In addition to the above interventions, we have made some key observations during this project and have recommended actions that could help to identify and assess the feasibility of geothermal projects and how to deliver these projects. The additional recommended actions summarised below would support the fledgling geothermal industry in NI.

Legislation

We recommend that legislation is reviewed to clarify status and ownership of geothermal energy and that a full regulatory framework is developed that enables licencing and permitting of geothermal resources and recognises the difference between "shallow" and "deep" geothermal.

Regulation

For shallow geothermal energy (SGE) we recommend that geothermal licencing is applied to open-loop GSHP system and to large closed-loop GSHP systems (e.g., > 200kW) but that smaller systems/horizontal loops would not require a project specific permit (for example, they could fall under a nation-wide general permit as long as standard minimum requirements are met). We further recommend a register of all systems that records location, type, capacity, and anticipated heating/cooling loads of each project.

A licencing system is recommended for the exploration and operation of deep geothermal energy (DGE) systems. Licences should specify ownership and conditions of use (including use of resource, environmental impacts, monitoring and reporting requirements, and decommissioning responsibilities).

Policy

Whilst there is currently a lack of legislation and regulation, and this will need to be addressed in due course, the fastest way to deliver projects is to provide certainty on revenue structures to encourage the investors who are willing to take on the risk.

We recommend that grant schemes are set up for SGE installations of all sizes. Indirect measures such as tax relief or changes to building regulations could also be considered for SGE systems.

For DGE systems we recommend that DfE engages in a consultation process with industry to identify which policy measures to prioritise. We have provided three options based on a Swiss, a Dutch, and a German model. These models include combined grant schemes, feed in tariffs, geothermal insurance schemes, and a loan scheme with risk sharing. Indirect measures for DGE systems include the development of mapping, funding to improve subsurface/reservoir understanding, sharing obligations, and of course, demonstrator projects.

1. Introduction

1.1 Project background

Geothermal energy is a scalable resource that has many applications for use from small spas, agricultural production, providing heating for homes to large scale power plants. Historically, geothermal energy has been limited to areas of volcanic activity and locations with high geothermal gradients. However, technological advances, mainly in the drilling sector, mean that deep geothermal energy can be accessed more cost effectively in areas with lower geothermal gradients. Providing further development and testing of these technologies, deep geothermal energy, may have the potential to be utilised in almost any setting. Furthermore, the introduction of heat pumps has enabled wider application of shallow geothermal energy applications as a viable energy resource in most geological settings.

In the EU, 30% of all energy consumed is used for heating, making up 79% of energy consumption in individual households [8]. In the UK, heating and hot water currently make up around 40% of the energy consumption and is responsible for nearly a third of greenhouse gas emissions [6]. Currently 68% of homes in NI are heated by oil boilers [3]. Heat is therefore a critical component of the UK's strategy to meet its decarbonisation targets [7]. Furthermore, the UK has a target to increase the number of homes on heat networks from 2% to 18% by 2050 [9].

In December 2020, the UK pledged to cut greenhouse gas emissions by at least 68% by 2030 [5] as a first step to achieve net zero greenhouse gas emissions by 2050. Northern Ireland has similarly legislated for an overall goal of achieving net zero carbon energy by 2050.

Geothermal energy has the potential to form an essential component of an energy mix required to achieve the UK's legally binding target of net zero emissions by 2050. Deep geothermal energy specifically could significantly contribute to the reduction of CO2 emissions in NI [23]. As air temperatures are expected to become warmer in response to climate change, the use of geothermal energy for cooling could also become significant.

Many governments in Europe and worldwide have recognised the potential of geothermal energy to make a significant contribution to the decarbonisation of heat and power as well as to other nationally important agendas such as energy security and job creation.

While geothermal energy remains largely absent from UK policy documents and renewable targets, the Energy Strategy for Northern Ireland [1] recognises that geothermal energy can contribute to the decarbonisation of heat and/or cooling. Within the Energy Strategy Action Plan [2] there is one specific geothermal related action (No. 16) to support the energy transition; 'to develop and commence delivery of a geothermal demonstrator project'. Another action (No. 15) is relevant; 'Develop and commence delivery of low carbon heat demonstrator projects'. Under the strategy, the government of Northern Ireland has established a Geothermal Advisory Committee to provide advice and guidance on the availability of geothermal energy and how to unlock the opportunities for geothermal heating and cooling.

Currently, deployment of geothermal technologies is underdeveloped in Northern Ireland. GSHP systems have been installed (exact quantity unknown) but there are no deep geothermal applications. However, there are many opportunities for geothermal projects across NI. Recent analysis of geological data by the Geological Survey of Northern Ireland (GSNI) has identified areas of Northern Ireland with potential for deep geothermal heating projects, in particular around Antrim and in other areas of deeply buried sediment by developing projects using the Sherwood Sandstone aquifer at depths of greater than 1km. In addition, shallow geothermal projects have been deployed across NI, from the current installations at Riddel Hall, Queens University Belfast to the boreholes drilled in 2010 at Ebrington Square, Derry/Londonderry.

High upfront capital costs, perceived, and actual risks (financial, geological) associated with geothermal development, together with a lack of incentives for geothermal technologies and a previous governmental scandal related to a renewable heat policy has meant that geothermal projects in Northern Ireland are lagging behind other renewables. This has created a knock-on effect in skills shortages, an immature supply chain and a lack of successful projects case studies. In order to develop confidence, encourage investment and increase the uptake in geothermal projects in NI, the GAC on behalf of the NI Department of Economy have commissioned a set of reports on geothermal energy.

Arup and the British Geological Survey (BGS) have been appointed by DfE to undertake research to understand the current geothermal energy sector in Northern Ireland. This project will be used to enable the development of a policy and regulatory framework that supports and promotes opportunities to unlock Northern Ireland's geothermal resource in the future.

1.2 Remit & Limitations

This report has been prepared specifically for and under the instructions and requirements of Northern Ireland Department for the Economy (our "Client") confirmed via an Engagement Letter dated May 11th, 2022, in connection with Research into the Geothermal Energy Sector in Northern Ireland based on tender ID 4024243.

The agreed remit includes:

- characterise the methods that could be used to harvest NI geothermal resources, including shallow and deep systems.
- identify the critical elements of different geothermal harvesting systems (e.g., closed, open, shallow, deep, stimulation etc.) and consider and compare the benefits and risks of each.
- quantify the potential decarbonisation, energy security, economic and environmental impact of each type of harvesting system.
- benchmark the cost basis for different elements of the geothermal system (e.g., drilling, heat pumps etc) as actual present-day costs.
- benchmark different types of system (e.g., closed ground source heat, deep enhanced geothermal systems etc) in a £/kW and £/kWhr.
- outline how policy, legislation and regulation can be designed to facilitate development of these resources and to mitigate risk for developer, consumers, the environment, and communities.
- detail policy/legislative/regulatory approaches taken in other nations of the UK and across Europe and their potential applicability in a Northern Ireland context.
- where feasible, identify the impact on jobs in the development and operation of geothermal in Northern Ireland.
- make recommendations on how Northern Ireland can accelerate the development of its geothermal resources with a particular focus on those sectors that where geothermal resources can have the biggest impact on decarbonisation of energy in Northern Ireland.

This report has been prepared for reliance by our Client for internal use. No third party is entitled to rely on this report. We do not in any circumstances accept any duty, responsibility, or liability to any third party whatsoever who has relied on this report. Accordingly, we disclaim all liability of whatever nature (including in negligence) to any third party other than to our Client.

In preparing this report we have relied on information provided by others, and we do not accept responsibility for the content, including the accuracy and completeness, of such information. In no circumstances do we accept liability in relation to information provided by others. Costs presented and technologies discussed reflect the status of the geothermal market at the time of writing.

We emphasise that any forward-looking projections, forecasts, or estimates are based upon interpretations or assessments of available information at the time of writing. The realisation of the prospective financial information is dependent upon the continued validity of the assumptions based at time of writing. Actual events frequently do not occur as expected, and the differences may be material. For this reason, we accept no responsibility for the realisation of any projection, forecast, opinion or estimate.

Findings are time-sensitive and relevant only to current conditions at the time of writing. We will not be under any obligation to update the report to address changes in facts or circumstances that occur after the date of our report that might materially affect the contents of the report or any of the conclusions set forth therein.

1.3 Abbreviations and Glossary

Abbreviations	
ATES	Aquifer thermal energy storage
BHE	Borehole heat exchanger
BTES	Borehole thermal energy storage
CAPEX	Capital Expenditure
DGE	Deep geothermal energy systems
EGS	Enhanced Geothermal Systems
GSHP	Ground Source Heat Pump
OPEX	Operational Expenditure
SGE	Shallow geothermal energy systems
SHR	Superhot rock systems
UTES	Underground thermal energy storage

Glossary	
Aquifer	Underground layers of water-bearing, permeable rocks that contain and transmit groundwater and from which groundwater can be extracted and discharged.
Aquifer thermal energy storage	Open-loop systems that use aquifers for seasonal storage and recovery of thermal energy in the subsurface. In summer, warm water is stored to provide heating in winter; in winter, cool water is stored to provide cooling in summer.
BEIS (UK Department for Business, Energy and Industrial Strategy)	UK Government department with responsibility for Business, Energy and Industrial Strategy. This includes science, innovation, energy and climate change policy. In the context of NI, energy policy is devolved and therefore policy set by BEIS may set a framework within which funding can be requested from HM Treasury, and in which NI policy can be made.
Borehole	Deep, narrow holes made in the ground, either vertically or inclined often for purposes to extract or to locate water, oil or other liquids e.g., oil and gas.
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.
Borehole thermal energy storage (BTES)	An array of boreholes configured underground. The ground heat exchanger array for a BTES system is designed and operated so that heat is stored or abstracted seasonally from rock or soil, essentially using the ground as battery.
CAPEX (capital expenditure)	This is the major spending required to drill and complete wells for long term use.
Closed loop GSHP	Systems that extract heat or cold from the ground by circulating a heat carrier fluid around an array of closed pipe loops (ground heat exchanger). These systems are typically installed vertically or horizontally at depth of less than 500m.
Coefficient of Performance (CoP)	The ratio of heat energy output relative to the electrical input required to drive compressors and pumps required for heating and cooling using heat pumps.
Committee for Climate Change (CCC)	An independent, statutory body whose purpose is to advise the UK Government and devolved administrations on greenhouse gas emissions targets.

Glossary	
Department for the Economy (DfE)	Lead department responsible for providing the strategic vision for the future of energy in NI, as well as key aspects of the energy legislative framework including the licensing and regulatory framework.
Department for Infrastructure (DfI)	NI Government department whose main responsibilities include regional strategic planning, roads infrastructure; water and sewerage networks; rivers and inland waterways; public transport; sustainable transport; active travel; air and seaports; vehicle regulation; and road safety. The Department's role in relation to the NI planning system includes planning legislation; regional planning and policy (including the Regional Development Strategy 2035 and Strategic Planning Policy Statement (SPPS)); and, supporting guidance, as well as the determination of regionally significant and 'called in' applications
Department of Agriculture, Environment and Rural Affairs (DAERA)	Lead NI government department for climate change.
Deep geothermal energy (DGE)	Term used widely to refer to systems at a depth of more than 500 m below the surface and generally where temperatures exceed 50°C. In this document, the term is used to refer to geothermal systems that are sufficiently hot for direct-use heating applications (without requiring a heat pump) or power generation.
Direct use geothermal	A system that is hot enough for geothermal heat to be used directly (for example for district heating) without requiring an electrical heat pump.
District heating	Communal heating systems that deliver heated water to a large number of homes and buildings via a heat network.
Ground source heat pump (GSHP)	A device that transfers and 'upgrades' subsurface heat from a colder space to a warmer space using mechanical energy. A heat pump can also function as an air conditioner to provide space cooling.
Enhanced Geothermal Systems (EGS)	Unconventional Geothermal systems which use the deep subsurface as a source of heat for the production of heat or electricity. Often referred to as hot dry rocks (HDR) They are at depth (~4-5km) created where there is hot rock but insufficient natural fluid and/or permeability within the system to transport this heat to the surface. Hydraulic fracturing is required to release heated fluid from the rock.
Hydrothermal systems (also referred to as 'hot sedimentary aquifers')	Geothermal systems that are heated by conduction containing fluid, heat and permeability in a naturally occurring geological formation or sedimentary basin for the production of heat or electricity.
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.
Northern Ireland Environment Agency	The NI Environment Agency is an executive agency within DAERA. One of the Agency's key priorities is to promote environmentally sustainable development and infrastructure. The Agency is the regulator of the Energy Savings Opportunity Scheme (ESOS) for organisations whose registered office is in NI.
Open loop GSHP	A geothermal system that typically pumps groundwater directly from an aquifer or flooded mine system via a production borehole and, after heat extraction, returns the water to the system via an injection borehole.
OPEX (operational expenditure)	This is the cost required to keep a heating/cooling system operational, including ongoing maintenance costs.
Sedimentary basin	Low areas in the Earth's crust, of tectonic origin, in which thick deposits of sediments accumulate over geological time periods.
Shallow geothermal energy (SGE)	Term used widely to refer to systems at depths of less than 500 m below surface. In this document, the term is used to refer to systems that use ground-source heat pumps.
Underground thermal energy storage (UTES)	A System in which hot water is pumped into underground boreholes, aquifers or caverns for the temporary storage of thermal energy and distributed according to energy demand.

2. Overview of Geothermal Systems

2.1 Geothermal systems

There are several different types of geothermal systems. These can broadly be split into two main categories: Shallow geothermal systems utilise low temperatures (10 to 25°C) and ground source heat pumps (GSHP), and deep geothermal utilise heat stored at depths providing temperatures that are sufficiently hot for direct-use heating application (without requiring a heat pump) or potentially for power generation. Both shallow and deep systems provide key contributions to the energy mix of the future, particularly in combination with other types of renewable energy resources and future technology developments. Advanced geothermal systems, for example, utilise very deep closed loops. They are an emerging technology which is made possible through ongoing advances in borehole technology, in particular precision directional drilling.

Northern Ireland’s geology is suitable for development of both, shallow and deep geothermal energy systems. A range of typical geothermal systems are illustrated in Figure 2.

Due to the lower cost and lower risks involved, shallow geothermal energy is more widely used than deep geothermal energy, although the heat output is considerably lower.

Both open loop and closed loop geothermal systems are possible in NI. An open loop system is where water is extracted from an aquifer directly for use and then returned to the aquifer through a reinjection borehole. A closed loop system is where a working fluid is passed through a piping network installed within the subsurface; the system is self-contained and does not remove or reinject groundwater.

2.2 Shallow geothermal

Shallow geothermal systems can provide energy for both heating and cooling and there is the potential for energy storage. They provide a low temperature, or low grade heat and rely on heat pumps to raise or lower temperatures for use in buildings. In most situations, these GSHP are used for smaller scale projects where individual or small clusters of buildings are heated or cooled by transferring energy in the form of heat. The energy can be transferred from or to aquifers (rock units) for open loop systems, or directly to the ground for closed loop systems. The size of a project is governed by both the building’s energy requirement and the energy available from the ground. It is noted that there is an increasing application of GSHP in low temperature heat networks, in particular 5th generation heat networks known as ambient loops. Ambient loop networks circulate low temperature fluids across larger areas and heat pumps within individual buildings connected to the network. They are used to meet the particular building energy demands, thus, maximising the efficiency of these systems when compared to higher temperature networks. Ambient loop networks can also be used for cooling.

Over the past decade there has been an increasing interest in utilising mine workings or mine water treatment schemes to provide a source of heat, cooling, or thermal storage. Due to the ongoing decarbonisation efforts mine water is being reviewed and investigated as a potential heat and heat storage source across Great Britain. Mine energy projects can utilise both open and closed loop systems and normally require a heat pump due to the relatively low temperatures, expected to be up to 20°C in NI. Due to the potential for high permeability in abandoned mines they are particularly well suited to open loop GSHP, however the hydrogeology of mine workings is often complex and environmental hazards need thorough consideration. They also benefit from being located near to residential and industrial centres which often formed around the mines meaning there is a demand for the heating/cooling.

2.3 Deep geothermal

The term deep geothermal energy (DGE) generally refers to accessible heat resources derived from depths greater than 500m below the ground surface [14] (>400m deep in some UK authorities). Importantly DGE requires specific geological conditions to be feasible and usually involves accessing high temperatures (>50°C) within the earth [10]. This includes having a source of heat that is accessible (through drilling) and carried via the fluid, and in the case of hydrothermal systems, having rock which allows sufficient water flow where the heat is located. Ideally the geothermal reservoir should be located below a low permeability rock which ‘caps’ the reservoir. Consequently, deep geothermal has traditionally been developed in countries like the United States, Iceland, New Zealand, Turkey, and Indonesia where geological conditions are conducive to produce heating/cooling and potentially electricity.

In volcanically inactive areas, deep geothermal projects are traditionally either hot sedimentary aquifers or enhanced geothermal systems (EGS). Hot sedimentary aquifers rely on the natural permeability of the ground to allow abstraction of hot groundwater to provide heating, and potentially electricity. EGS are used in areas of hot igneous/crystalline rocks which generally have a low natural permeability and therefore hydraulic stimulation is usually needed to increase the permeability by developing the fracture networks. Advances in EGS technology have made this system more accessible. Examples of projects in the UK and Europe are the United Downs Deep Geothermal Project in Cornwall, the Soultz-sous-Forets site in France and the Gross Schoenebeck site in Germany.

In Europe, deep geothermal energy is being utilised for heat e.g., the Paris Basin hydrothermal district heating network and geothermal greenhouses in the Netherlands. Recently, deep geothermal wells have become more focused on producing power at lower temperatures (using a binary plant operated through a conventional Rankine cycle) and direct heat together (i.e., Combined Heat and Power (CHP) Plants) e.g., Germany and Netherlands. Deep geothermal can provide direct heat and, in certain specific conditions, electricity (where the temperature is above 100°C and the formation can produce water fast enough). The required temperature depends on technology option; direct dry steam plants (>150°C), flash plants (>180°C) or binary plants (100 - 170°C) [123].

The risk profile for a typical deep geothermal project is presented in Figure 1. The investment risk only reduces once resource is proven via initial drilling investment [14]. The risk of project failure for deep geothermal is higher for two key reasons:

1. Typically, there is limited information on the deep geology, in particular low confidence in permeability and fault characteristics.
2. Drilling complexity and requirements for higher cost specialist drilling equipment.

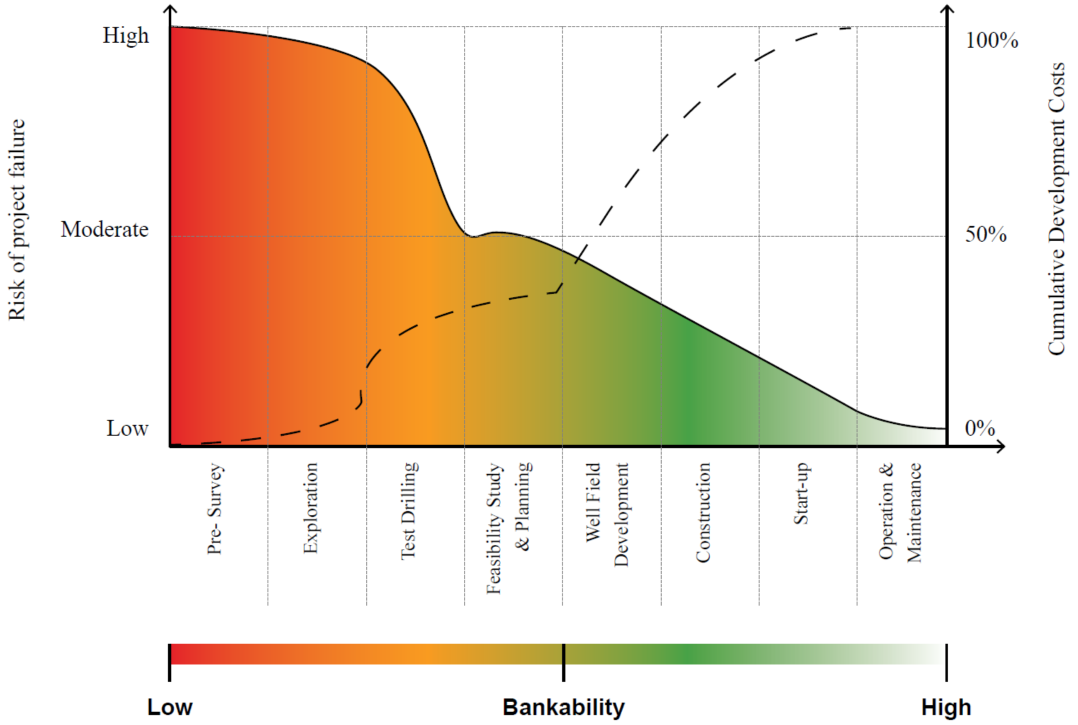


Figure 1 Geothermal Project Cost and Risk Profile at Various Stages of Development (World Bank, 2012)

Northern Ireland has the skills (engineering, knowledge, experience) to overcome the challenges associated with accessing the hot geothermal fluids deep within the ground. Deep wells are required, and these wells need to encounter not only geothermal fluids which are hot enough, but also at locations where the ground is permeable enough to sustain pumping of the fluids to the surface (and introduced back to the subsurface). Based on the known geology, there is significant potential for deep geothermal projects in Northern Ireland, particularly heat projects.

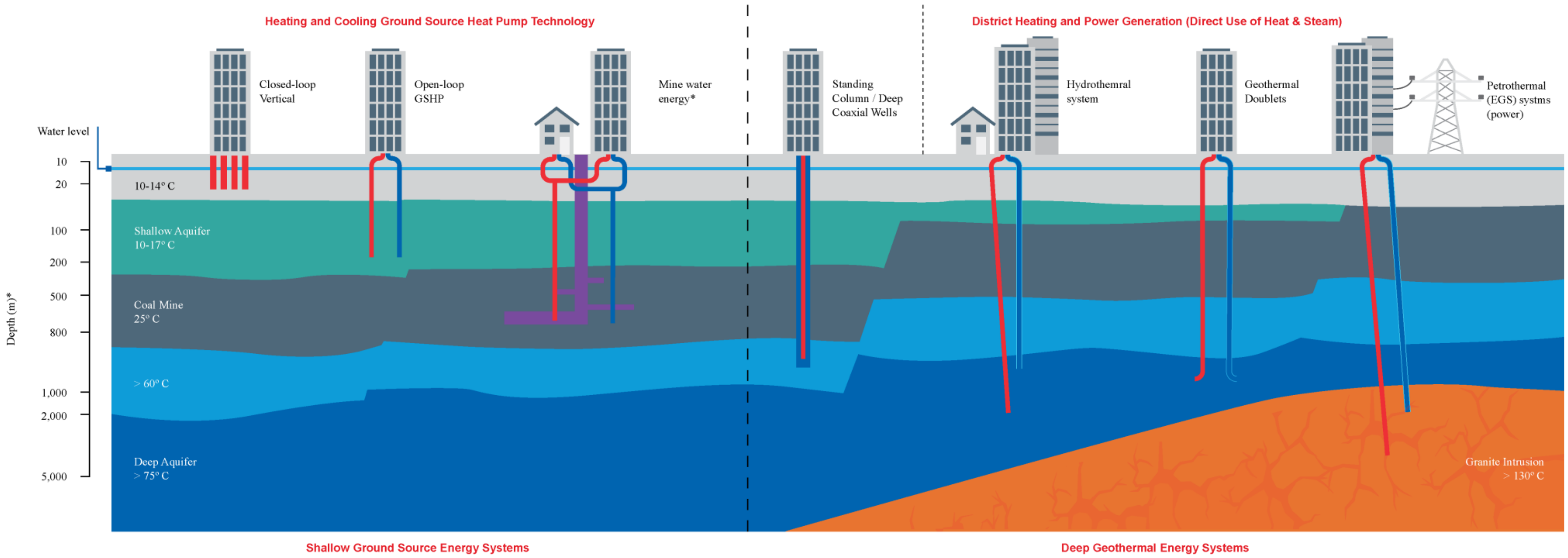


Figure 2 Illustration of typical geothermal project types (Arup ©) [13]

3. Northern Ireland Geothermal Conceptual Model

3.1 Approach

In line with the remit of this review, a high-level geothermal conceptual model has been developed (Figure 9) to underpin the assessment of shallow and deep geothermal potential across Northern Ireland and help identify which geothermal systems might be applicable under different geological scenarios, in particular open loop GSHP systems and deep geothermal.

Information supplied by the Client and published data was reviewed to develop the conceptual model. This included geological, hydrogeological, and mineral data via the GSNI GeoIndex [10].

Based on the review of available data, and consistent with an assessment made by the GSNI, Northern Ireland's bedrock geology has been simplified into four regions as shown on Figure 3 and detailed in Table 1 [21]. For this geothermal conceptual model, we have focused on rock types and conditions that are most suited to geothermal projects. These are sedimentary rocks that can form aquifers capable of groundwater flow and igneous rocks, in particular those with known permeability such as the Antrim Lava Group, and plutonic rocks that are often areas of higher geothermal gradients owing to radiothermal heat.

Table 1 Summary of Northern Ireland's bedrock geology

Region number	Location	Geological component	Summary
1	Northwest	Mesoproterozoic to Silurian	The Sperrins dominate the landscape in this region and predominately consist of the Dalradian Supergroup (psammite, quartzite, semipelite, pelite, limestone) and metamorphosed basic igneous rocks. The base of the Sperrins is within the Tyrone Group of limestone and mudstone. There are small pockets of Roe Valley Group consisting of mudstone, limestone and siltstone.
2	Southeast	Ordovician to Silurian	The region lies within a drumlins landscape. Bedrock most common to the region is the Gala and Hawick Groups composing of Wacke sandstones, thin-to medium-bedded greywacke and interbedded silty mudstone with thin red mudstone beds. The Mourne region to the south is part of the Newry Igneous Complex of granite and granodiorite.
3	Southwest	Devonian to Carboniferous	Dominated by the Tyrone Group of limestone and mudstone, the region also has a central area composing Fintona and Cross Slieve Groups 'Old Red Sandstone' of sandstone and conglomerates with mudstone. This region consists of sub-sections with Coal Measures and Millstone Grit Groups containing mudstone, siltstone, sandstone, and coal. There are some minor outcrops of Sherwood Sandstone Group.
4	Northeast	Permian to Palaeogene	Shallow bedrock in this region is predominantly the Antrim Lava Group or Upper and Lower Basalts. The Mercia Mudstone Group is located along the north of Belfast Lough which consists of mudstone, siltstone, and sandstone with rock salt (halite). Along the northeast coastline there is a combination of schist, marble, phyllite from the Neoproterozoic era and some chalks and limestone. Belfast and the wider area are dominated by the Triassic Sherwood Sandstone Group of sandstone, siltstone, and mudstone.

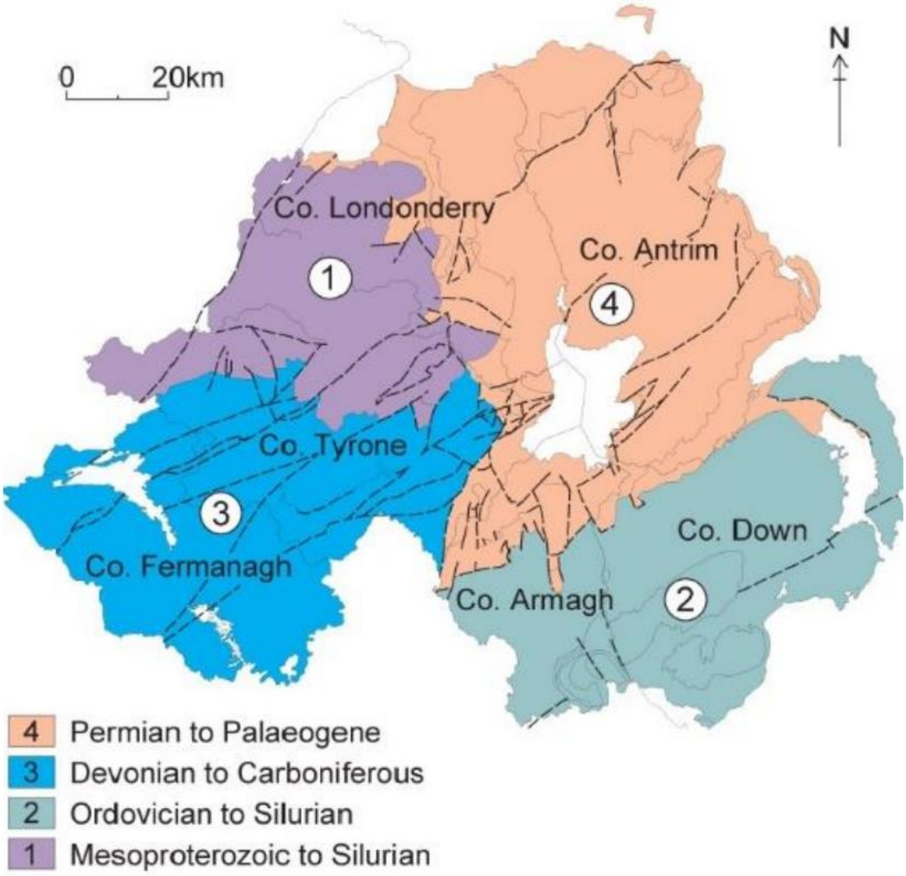


Figure 3 Major geological regions of Northern Ireland and inferred rockhead faults, duplicated from [20][21]

The superficial geology across Northern Ireland is relatively thin and highly variable, with composition and depth depending on the region and local geomorphology. Arup ground investigations across Northern Ireland have recorded superficial deposits from ground level to around 35m depth, location dependent. Predominantly there are glacial sediments, which include clay, silt, sand, and gravel, known as glacial till. However, locally superficial sediments include fluvial, lacustrine, estuarine and alluvial deposits from lakes, rivers, estuaries, and coastlines, and on higher ground, particularly in the north and west of the country, there are peat bogs. Generally, the superficial deposits are soft and easily eroded except glacial till which is often a very stiff clay.

The nature of the superficial deposits is specifically relevant to very shallow systems (such as slinky and closed loop boreholes – see Section 4 for further details). In most situations, these technologies will work regardless of the geology and therefore, for the purpose of this conceptual model, the superficial deposits have not been assessed in detail. Nonetheless, project specific assessment of the superficial deposits is recommended; these deposits need to be characterised properly for cost efficiency during construction and to ensure the correct casing and drilling technique is used.

3.2 Bedrock geology

3.2.1 Sedimentary aquifers

The key sedimentary aquifers within Northern Ireland which have the potential for open loop systems are;

Triassic – Sherwood Sandstone Group

Permian – Belfast and Enler Groups

Carboniferous – Primarily Coal Measures and Millstone Grit Groups

A simplified geological map presented in Figure 4 shows where these aquifers occur at the surface (outcrop) or immediately below superficial deposits (sub crop).

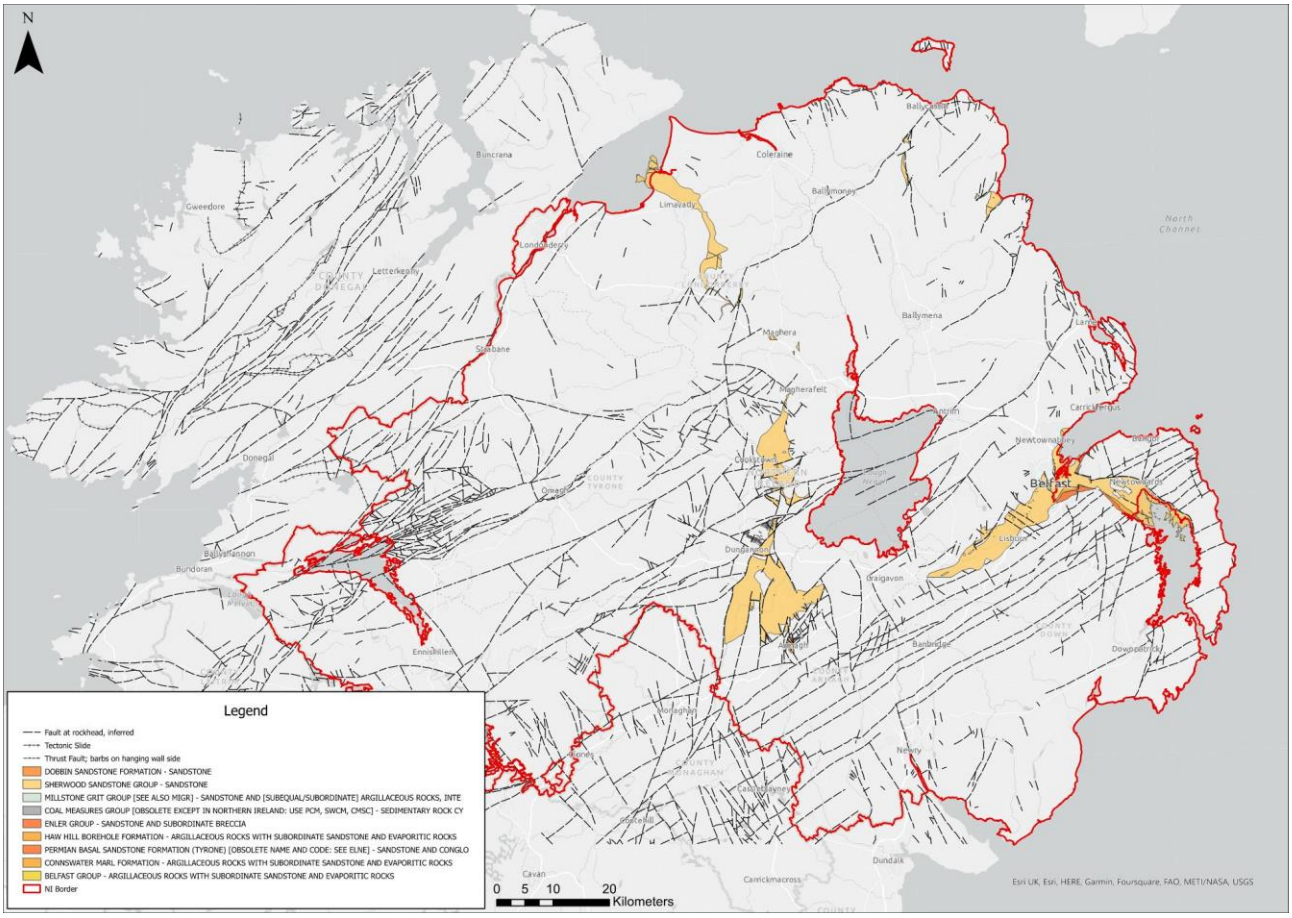


Figure 4 Location of Sedimentary aquifers at surface and main fault lines

Triassic - Sherwood Sandstone Group

The Sherwood Sandstone Group, located at surface in areas to the northeast and southwest of Northern Ireland as shown on Figure 4, comprises friable yellow or red sandstone and is classified as a high potential productive aquifer with fractures and intergranular flow. Figure 5 shows the estimated depths to the top of the Sherwood Sandstone Group across Northern Ireland overlain with fault lines. Figure 5 shows that the Sherwood Sandstone Group is located to the north and centre of Northern Ireland. It extends to depths greater than 3000m in the Antrim and Lough Neagh areas and is shallower on the edges of the strata.

The Sherwood Sandstone Group occurs in the Rathlin, Larne and Lough Neagh basins. The Larne No. 2 borehole recorded Sherwood Sandstone Group with a thickness of 800m and at a depth of 1800m [23].

Based on gravity modelling and seismic surveys Raine & Reay 2019 [107] estimates that the Sherwood Sandstone Group is >2000m deep in the Lough Neagh Basin, and >1500m deep in the Rathlin Basin. Based on this study the Sherwood Sandstone Group is a likely resource for deep geothermal energy.

Permian – Belfast and Enler Group

The Permian sequences are divided into Lower and Upper Permian; Lower being the older Enler Group and upper the Belfast Group. Permian outcrops are limited across Northern Ireland but noted at surface in Cultra, Ballyrainey and Armagh City [24] . A borehole in Belfast Harbour has recorded Permian deposits nearly 135m thick, while the Larne No. 2 borehole recorded approximately 440m of Permian sandstone between 1800 and 2200m depth [23]. Generally, the Belfast Group overlays the Enler Group, and as the Sherwood Sandstone Group is from a younger era it tends to overlie the Belfast and Enler Groups.

Carboniferous – Primarily Coal Measures and Millstone Grit Groups

Rocks of Carboniferous age are predominantly identified in the Dungannon area but are also present in the Lakelands of County Fermanagh. These older sedimentary rocks include limestones, sandstones, mudstones, and some shallow coal seams. In the Kilcoo Cross and Slisgarrow boreholes, carboniferous deposits up to 150m thick have been recorded between 1600m and 1800m depth [23].

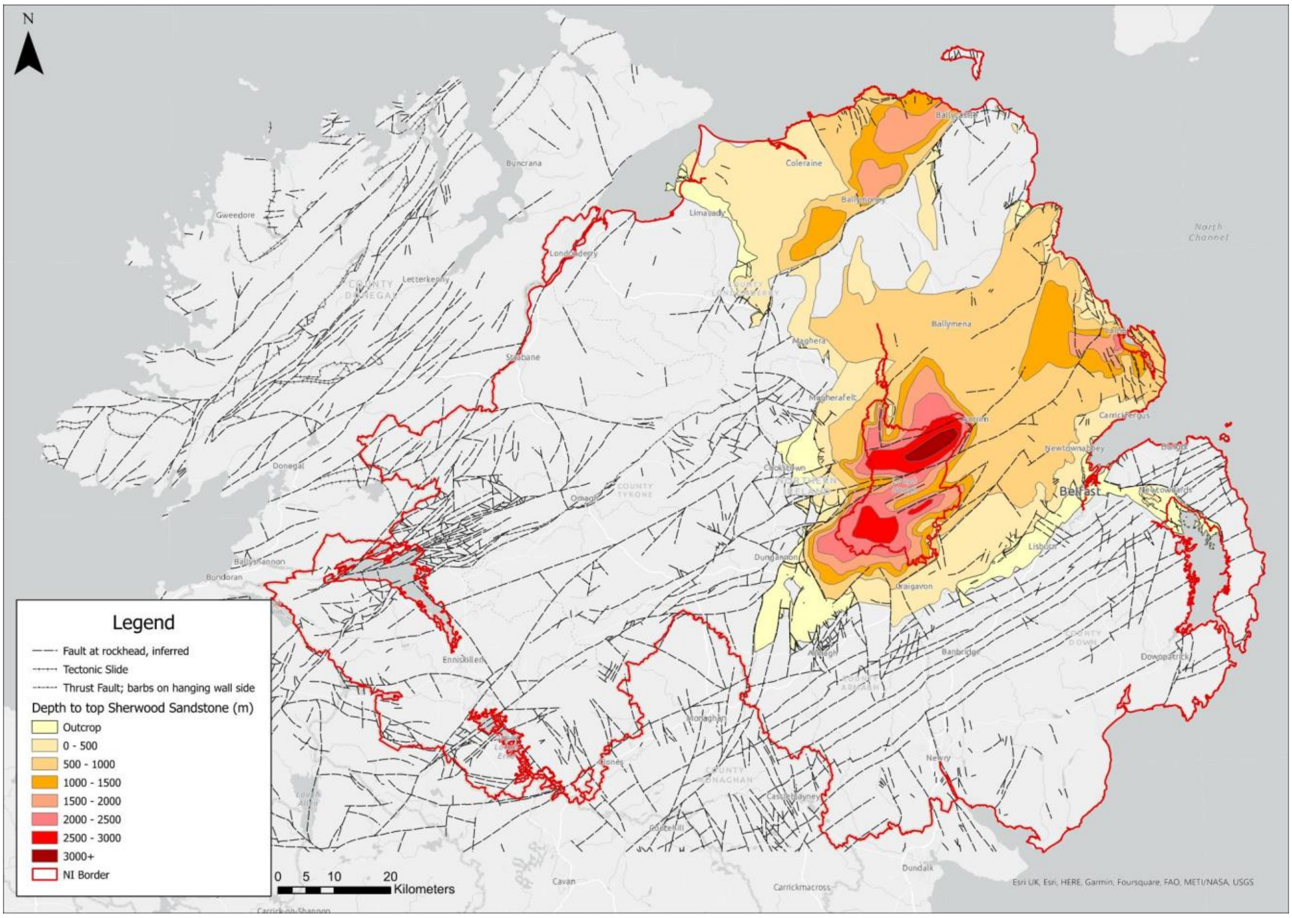


Figure 5 Predicted depth to top of Sherwood Sandstone Group and the main fault lines

3.2.2 Igneous Rocks

Igneous rocks in the region are formed from molten lava originating from great depths during the Palaeogene period. Basalt is an extrusive rock which erupted onto the earth's surface whereas granite is intrusive and solidifies below the earth's surface.

Generally, igneous rocks have low permeability, however depending on their fractures and faults they can be permeable. Basalt and granite locations, where they are encountered at surface or immediately below superficial deposits, are shown on Figure 6. Notably the sedimentary Lough Neagh Group directly overlies the Antrim Lava Group and may be a considered a separate geothermal resource. Igneous rocks are detailed further in the following sections.

3.2.2.1 Palaeogene Igneous Rocks – Basalts

Antrim Lava Group: Basalts of the Antrim Lava Group are abundant in the northeast of Northern Ireland. They are split into Upper and Lower Antrim basalts separated by an interbasaltic layer. There are a number of abstraction wells installed within these which have been tested and prove that the fractures allow significant water flow. These basalts range from 100 to 750m thick [21].

Dykes: The Tellus survey [10] revealed large numbers of intrusive igneous dykes, mostly in County Down, County Tyrone and County Fermanagh. There are four distinct dyke swarms which are broadly aligned to NE-SW to E-W directions [115]. These are typically less than 10m wide, although they can be as wide as 90m.

3.2.2.2 Palaeogene Intrusive Centre – Granites

The buried granites in Northern Ireland may be a potential source of geothermal energy, specifically for EGS [21], however there is a lack of information on these reservoir properties.

Mourne Mountain Complex: The granites and related rocks of the Mourne Mountains are formed from five different granite intrusions, evident in the mountain peaks and ridges, up to 800m high.

Slieve Gullion Complex: The granites and related rocks of the Slieve Gullion Complex were formed as large masses, hundreds of metres thick, from the solidification of molten rock below ancient volcanoes. Slieve Gullion is a 573m mountain consisting of three different granite intrusions. Notably, the Carlingford Complex (which is entirely within the Republic of Ireland) is located very nearby, approx. 1km.

3.2.2.3 Late Palaeozoic Intrusive Rocks – Ordovician

Tyrone Igneous Complex: These rocks are categorised as both Tyrone Plutonic and Volcanic Groups. The Tyrone outcrop is bounded in the north by the Omagh Thrust fault and by the Beleevnamore and Davagh faults in the south [103].

Newry Igneous Complex: The Newry igneous complex is composed of three plutons; Rathfriland (northeast), Newry (central), and Cloghoge (southwest) plutons [118]. It is expected that the Newry Complex has low to intermediate heat production characteristics, and therefore offers low potential for geothermal energy [120]. However, further testing is needed before discounting this geothermal resource.

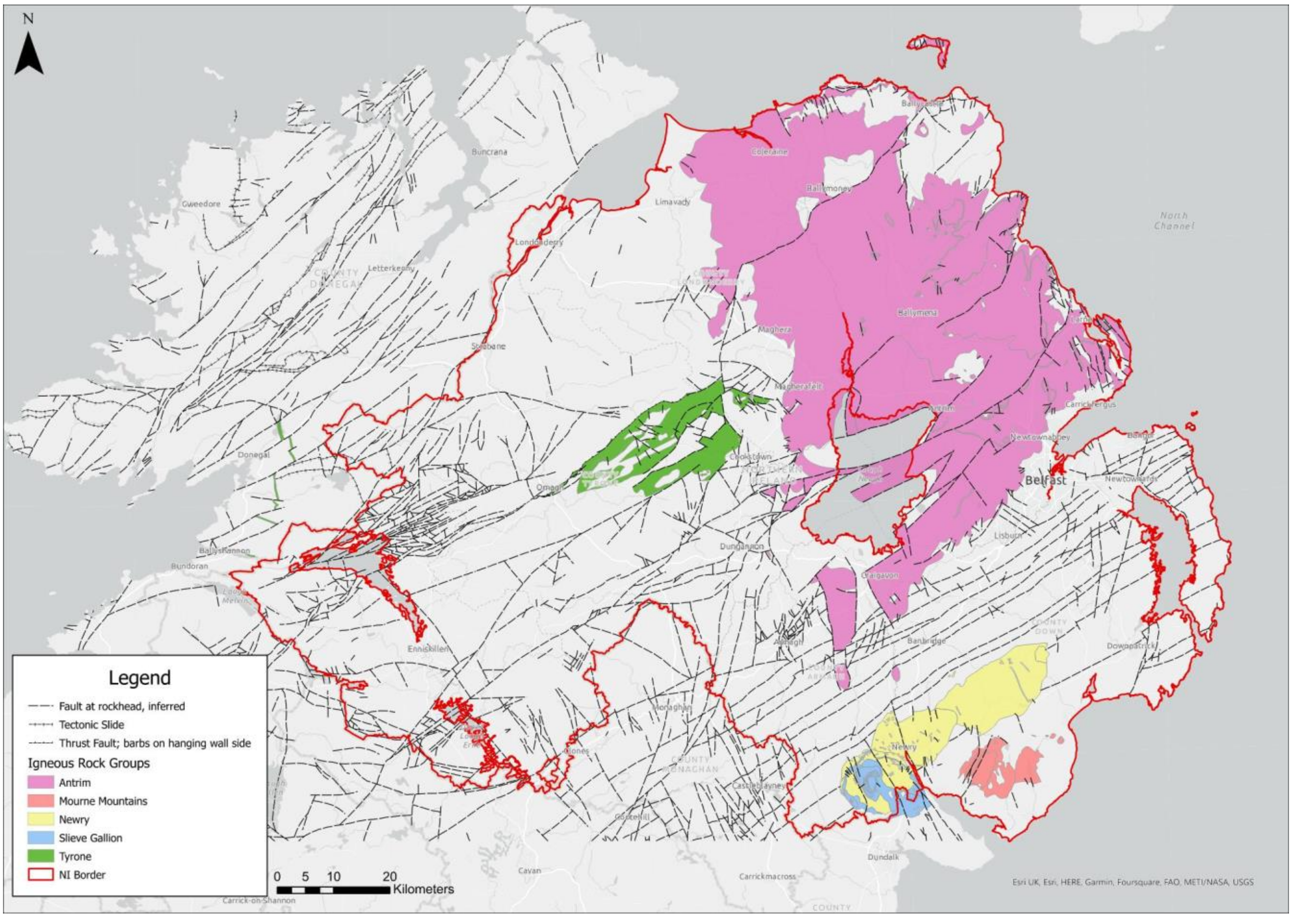


Figure 6 Location of the Igneous Complexes at surface and the main fault lines

3.3 Thermogeology

There is currently limited information about the deep geology across Northern Ireland, specifically, detail on the presence of fractures which can allow geothermal fluids to flow at sufficient quantities for a viable geothermal project and aquifer permeability. As shown on Figure 8, there are limited deep boreholes across Northern Ireland. Following a review of data provided by GSNI, only fifteen of these boreholes have temperature data. The temperature distribution at depths across the province needs to be confirmed to better understand the deep geothermal potential. While desk-based studies and remote surveys (such as surface geophysics) can reduce the geological risk associated with deep geothermal projects, the risk remains high in the early project stages and only reduces considerably once the first borehole is drilled, and the conceptual geothermal model is proven (see Figure 1). This is expensive and requires upfront investment.

Shallow geology across the province is better understood as there has been significant geotechnical investigation for developments.

The remit of this report did not include a detailed assessment of the thermogeology across the province, therefore only a high-level summary is provided below. There are a number of reports, papers and maps already published on this topic.

3.3.1 Sedimentary geothermal potential

Raine & Reay 2019 [107] states that where temperature data is available, geothermal gradients in the sedimentary basins have been estimated in the range of 28 – 34°C/km. At depths of 2000m below ground formation fluid temperatures are expected to be 80°C, a well in the Rathlin Basin (Ballinlea No. 1) recorded a temperature of 97.8°C at 2565m depth.

A study undertaken in collaboration with Arup [105] reported that the Larne Basin is likely to have a reservoir temperature of 83°C with 2,060PJ stored heat and a heat potential of 510MWth. This report estimated that a hydrothermal direct heat well in Lough Neagh basin to 2000metres below ground level could produce 5MW gross capacity.

The Permian and Carboniferous Sandstones are less well known but both promising reservoirs. The Permian Sandstones have been proven to be productive aquifers through pumping test results [107].

In summary, published data indicates that the Sherwood Sandstone Group (Rathlin, Larne and Lough Neagh basins) is a likely resource for deep geothermal energy. The Permian and Carboniferous Sandstones are marginally less promising but strong secondary targets [107]. Any shallow sandstone aquifers may also be suitable for open loop GSHP.

3.3.2 Igneous geothermal potential

Basalts are generally impermeable but fractures have created permeability. Fractures with significant water flow have been recorded in the Antrim Basalts and a number of productive abstraction wells have been installed in this strata. Investigation is required to further quantify the resource.

It is expected that the Mourne Mountains Granite Complex has a heat production value of 3.69-7.21μWm-3 with projected temperatures at 5000m depth of ~114°C [108]. From 2D resistivity models it is anticipated that these granites extend to depths of 3km in the west and 8km in the east of the Complex.

In summary, published data indicates that the Antrim basalts are a likely resource for shallow geothermal energy. There is limited knowledge of the reservoir properties of the granite intrusions (Mourne Mountain and Slieve Gullion Complex) so further investigation is required but they may provide temperatures suitable for EGS.

3.4 Mine workings

There are numerous coal mine workings across Northern Ireland which are potentially flooded and offer a resource for heating/cooling and thermal storage. Figure 7 shows the location of all mining across Northern Ireland with specific commodities identified via a label, notably there are two coal mining areas near Dungannon (Tyrone) and Ballycastle (Antrim). Raine and Reay (2021) includes a more detailed map showing the mining districts across Northern Ireland. The Ballycastle mines are shallower than the Dungannon mines, which are up to 330m deep. However, the mine water temperatures are not recorded, and the status of these mines is currently unknown. From geological records [103] it is understood that the Ballycastle coal seams reach depths of 200m below ground. If these mines are flooded, they offer the potential for shallow open loop geothermal, i.e., using a GSHP, due to the likely high permeability of the mine workings. The deeper mines at Dungannon are likely to provide a higher coefficient of performance (CoP) for heating due to the expected higher temperatures at greater depths.

There exists some potential for mine water heat and heat storage particularly within deeper mine workings, such as Dungannon that may be suitable for industrial, horticultural and district heating use [21]. However, managing risks associated with mine hazards and mine hydrogeology is particularly complex. Consequently, further investigation work will be required to deduce whether mine water heat in Northern Ireland can offer an economic supply of heat compared to an alternative option such as aquifer heat. Mine energy is more likely to be sourced from an extensive mining network over several depths.

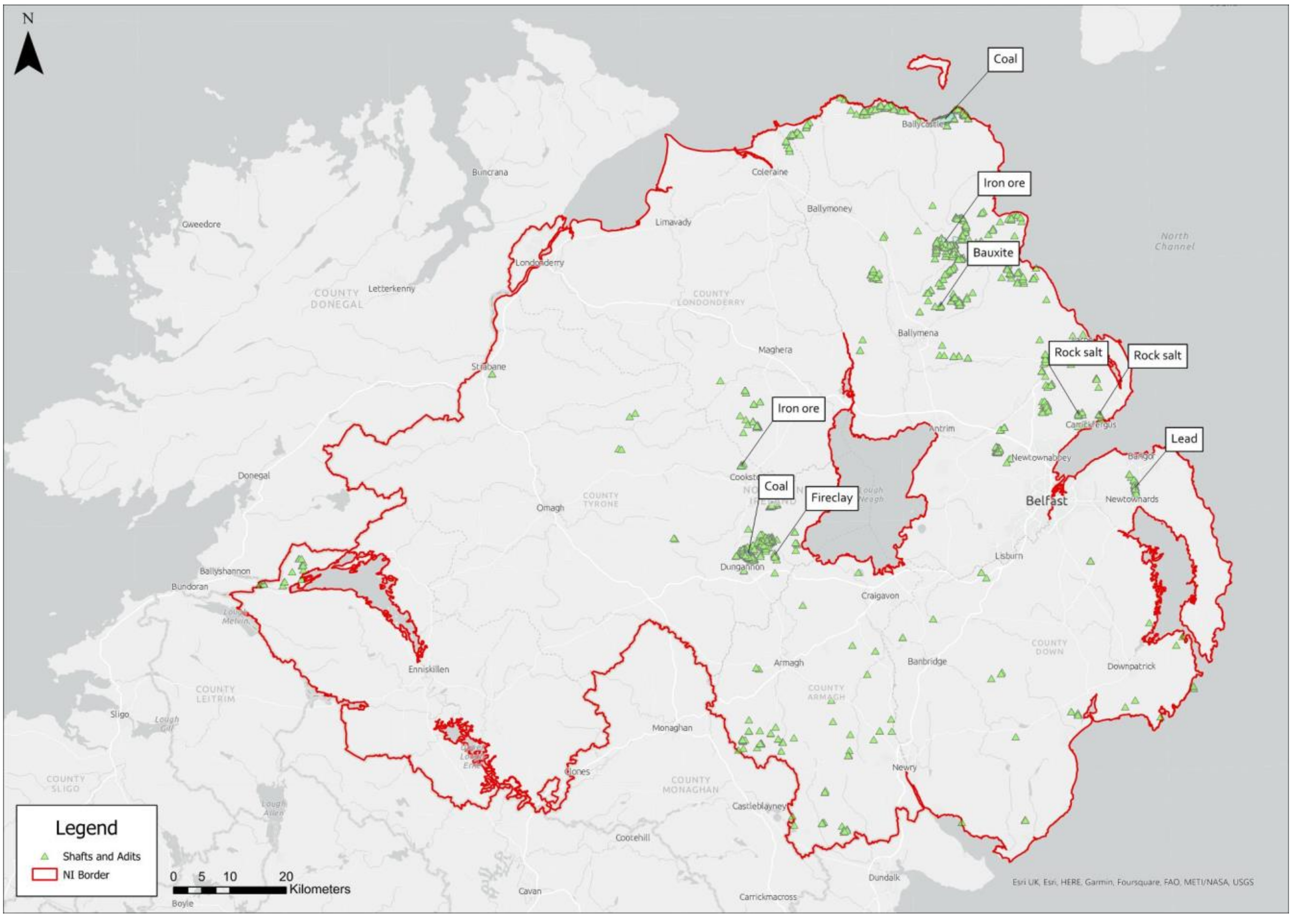


Figure 7 Historical mining areas in Northern Ireland [10]

3.5 Oil and Gas wells

Across Northern Ireland, but particularly towards the northeast and southwest, there are a number of deep wells (500m) as shown in Figure 8. Fifteen of these are hydrocarbon exploration wells which have recorded temperature information. The wells were targeting the Permian Sandstones and Sherwood Sandstone lithologies in the Rathlin and Lough Neagh basins at 2000m. Goodman et al (2004) modelled these temperatures and mapped potential thermal gradient profiles against depths across Northern Ireland [22]. Temperatures at 2500m depth across NI were assumed to be 60 - 100°C, with the warmest temperatures close to Ballycastle and Dungannon [22].

Considering the temperatures recorded in these oil and gas wells, there could be a future opportunity to modify and convert them to provide geothermal heat using new technology being introduced into the market. At present, the economic case for repurposing of hydrocarbon wells for geothermal use has not been proven.

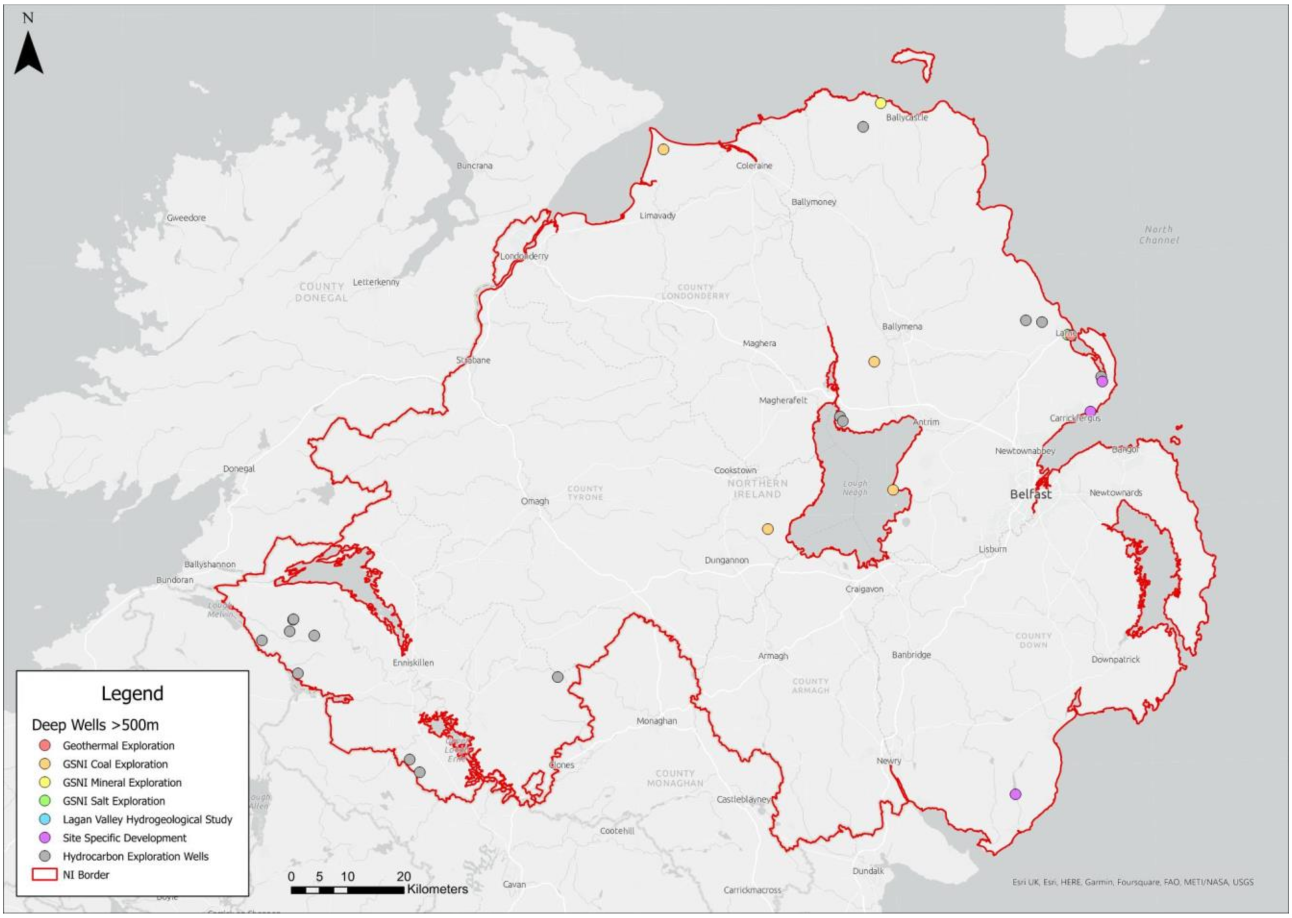


Figure 8 Historical non-petroleum and hydrocarbon exploration wells in Northern Ireland [10]

3.6 Conceptual geothermal model

A schematic conceptual geothermal model illustrating the key geological features found in Northern Ireland and the main geothermal technologies suitable is presented in Figure 9. Further detail for all shallow and deep geothermal technologies reviewed for this study is presented in Section 4.

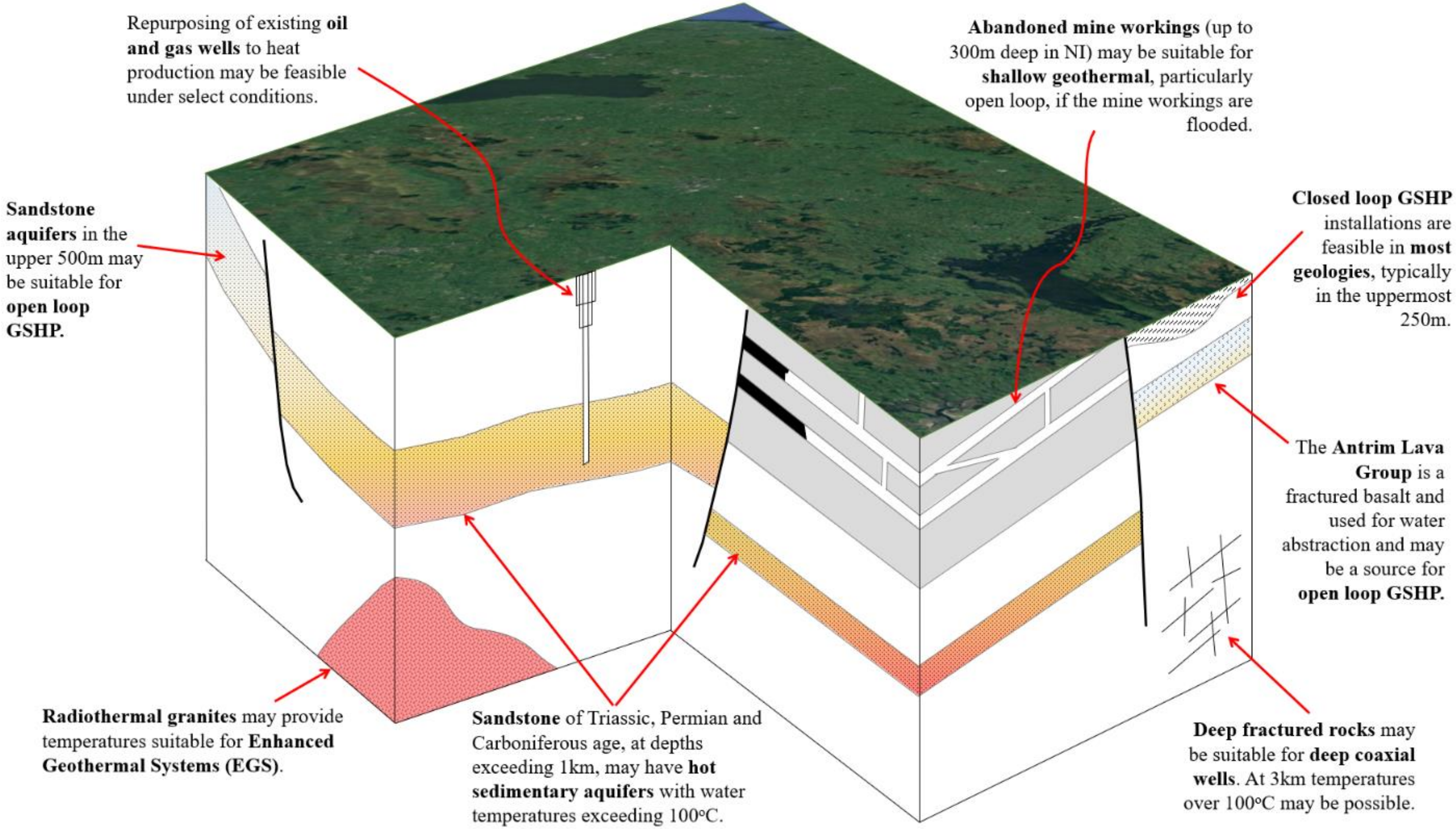


Figure 9 High level conceptualisation showing some of the key geological features of Northern Ireland that are applicable to shallow and deep geothermal technologies

4. Technology assessment

4.1 Overview

There are several technologies available to access geothermal energy at different depths and in different settings. Some technologies are widely used and well understood, for example, shallow geothermal energy accessed via closed loop vertical boreholes. A review for each the technologies is listed in Table 2 and is presented in Section 4.2 and 4.3 (which describes the characteristics and critical elements of each technology).

Included in this review are details on how the technologies work, depth range, suitability, ground temperature as well as commentary on the economics and environmental impacts specific for Northern Ireland. The geothermal opportunities are conveyed in terms of energy capacity, capital requirements, and project risks. The review details the Coefficient of Performance (CoP) for Ground Source Heat Pump (GSHP) systems based on heating and output temperatures up to 65°C, which is typical of temperatures required for buildings. For the deeper geothermal systems, where heat pumps are not typically required, a cost per unit energy has been provided as an alternative to CoP. It is possible to boost a deep geothermal system with a heat pump but that has not been considered within this report. Temperature ranges provided are based on the average geothermal gradient in Northern Ireland which is expected to be between 28 and 34°C/km depth [107].

Carbon savings presented in the tables below are based on emissions compared to a gas boiler providing the same energy. These are based on greenhouse gas carbon emission factors of 0.18kgCO_2/kWh for grid methane and 0.23kgCO_2/kWh for grid electricity [26]. Whilst the electricity grid factor is higher than gas, a heat pump has a high efficiency meaning the energy required to deliver the same heat output is much lower. This is a function of the CoP which is the ratio of the heat energy output per unit of electrical energy. Note that the carbon required to construct the geothermal system (including the embodied carbon) has not been factored in this assessment.

Table 2 Shallow and Deep Technologies

Shallow geothermal	Deep geothermal
GSHP: Closed loop horizontal slinky	Hot Sedimentary Aquifers (Hydrothermal Systems)
GSHP: Vertical closed loop	Deep Coaxial Single Well
GSHP: Single Coaxial Wells/standing column wells	Advanced Geothermal System (AGS) (Deep closed loop – e.g., Eavor systems)
GSHP: Open Loop	Enhanced Geothermal System (EGS)
GSHP: Mine water open loop/closed loop	

This review is limited to the list of technologies in Table 2, however there are a number of other geothermal systems being evaluated and utilised in other countries. These additional technologies include, but are not limited to:

- **Superhot Rock (SHR) Systems**: An ultra-deep geothermal technology called Superhot Rock Systems are a deeper variety of hot dry rock systems and are currently developing interest. SHR systems may provide an opportunity in Northern Ireland in the future, however, as research is still ongoing and due to the infancy in deployment of this type of system it has not been included in the technology review. Innovations are still needed to commercialise this system including developing drilling technologies that can economically drill to target depths in hard rock with high temperatures [89]. The depth of a SHR system is site specific but may be deeper than 7 km below ground and within high crystalline rock. However due to drilling limitations SHR systems have only been completed to depths between 3 and 7km below ground.

- **Underground Thermal Energy Storage (UTES)**: Underground Thermal Energy Storage is the use of the ground to store waste or surplus heat/cooling for use at a later time. This storage can increase the overall efficiency of heating/cooling systems. UTES can be paired with a GSHP if required. While UTES provides a convenient form of bulk thermal energy storage, the success of large-scale systems is largely dependent on the hydro/geological conditions as well as on a local need for district heating [41] or an industrial application. Often UTES is referred to as Aquifer Thermal Energy Storage (ATES), i.e., an open loop system or Borehole Thermal Energy Storage (BTES), i.e., a closed loop borehole system. UTES may be an opportunity in Northern Ireland in the future, however, as research is still ongoing into Northern Ireland's aquifer properties, UTES has not been included in the technology review.

4.2 Shallow geothermal technologies

GSHP: Closed Loop *Horizontal* Slinky

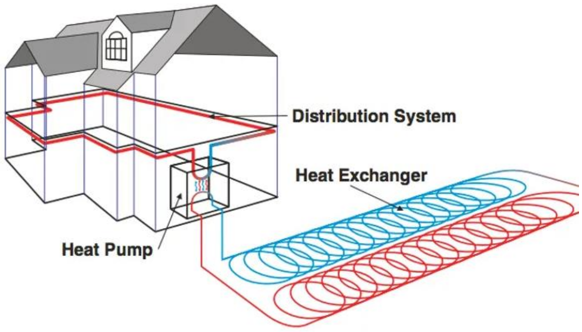
Summary of technology

Closed loop system whereby the working fluid is contained within the 'slinky' pipes installed in the ground within trenches. The fluids do not interact directly with the subsurface and heat is transferred with the ground via conduction.

Horizontal loop systems are typically installed in 1 to 2 m deep trenches within the ground, which can be less expensive than installing vertical loops but will use more land space.

System consists of the underground heat exchanger and piping network, heat pump/heat exchanger, and building distribution system.

Additional costs may need to be factored for landscaping works following installation of the loops, and/or future proofing against root growth.



Source: North Dakota State University [36]

Typical System Details

Depth range	Up to 5m for horizontal loops.
Suitable geology	Superficial deposits and outcrops across NI.
Ground temperature	10 to 12ºC [12].
Application	Space heating, hot water, and cooling.
Scale of energy available	Can be applied in many geological settings, in soil and superficial deposits but unlikely to be suitable in rock as excavation costs may increase significantly. Applied to many buildings in cities all around the world but more common in rural areas. The scale of the energy available is dependent on the land available to install the loops. Installation of larger systems up to 150kW are best in areas where land is plentiful [12].
Coefficient of performance (CoP)	For systems built for heating and cooling purposes, a CoP of around 3 for heating and 6 for cooling [12].
Carbon saving potential	Based on a CoP of 2.5 to 3, the carbon savings for heating compared to a gas boiler is around 0.09 to 0.1 $kgCO_2$/kWth which is around a 50 to 60% saving, resulting in savings on heating bills and reduced reliance on gas in the winters. The investment pay offs are slower ~10 years (compared to non-geothermal). Works best in new buildings and in particular underfloor heating. Existing buildings may require retrofit to reduce thermal losses and to upgrade internal heating systems.
Order of magnitude CAPEX	Pipework suggested cost of around £1k to 5k per km for materials and installation, or £1,250 - £1,750 per kW of capacity [13].
Key risks	The building heating and cooling requirements must be balanced enough to allow sustainable energy delivery. In cases where more energy is used than the ground can sustainably provide, the system can become inefficient to the point of unusable, which is dependent factors such as, building energy loads (and relative balance), thermal capacity of ground, thermal coupling to ground or aquifer, ground connection engineering, heat transfer between ground and heat pump, heat pump type, size and efficiency, system controls up to interface with building [12]. Competent site assessment, design and system implementation are key to preventing failure.
Testing requirements	Design: ground investigations (soil classification) and thermal response testing. Design must include system sizing based on heating and cooling requirements to ensure energy delivery for life of project, development of testing requirements during installation and interface with building control systems. Construction: the Ground Source Heat Pump Association (GSHPA) standards are available for detailed requirements including pressure test requirements, flushing, purging and dosing, performance verification for all operation modes, snapshot and seasonal and system optimisation [12].
Environmental impacts	Limited. However, pipework will permanently remain in the ground.

GSHP: Vertical Closed Loops

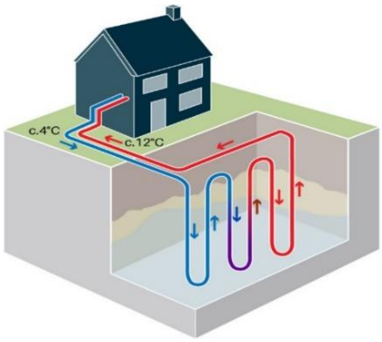
Summary of technology

Vertical loops pipes are fitted in boreholes installed to depths between 50 and 200m below ground level [12] configured in arrays/lattice patterns.

Generally, more common than horizontal systems due to space efficiency, especially in cities with less space available and higher energy demands.

System consists of the underground heat exchanger and piping network, heat pump/heat exchanger, and building distribution system.

Manifolds are used to connect the borehole arrays.



Source: BGS [37]

Typical System Details

Depth range	Typically, up to 200m [12] (although deeper boreholes are becoming more common).
Suitable geology	Superficial and bedrock geology across NI, typically within the uppermost 200m. Harder rocks may be less cost effective due to additional drilling costs.
Ground T	Around 10 to 14ºC up to 200m depth [12].
Application	Hot water, space heating & cooling, small scale district heating or larger scale ambient loop networks.
Scale of energy available	Can be applied in most geological settings. Applied to many buildings in cities all around the world. The scale of the energy available is dependent on the land available to install the loops and building demands. A single borehole to 200m would be expected to provide around 7.5kW (as baseload energy) to 12kW (as peak energy) on the ground side (i.e., without accounting for CoP). However actual capacities will depend on building demands and ground conditions.
CoP	For heating & cooling systems, a CoP in the range 3 to 4 for heating and around 6 to 8 for cooling [12].
Carbon saving potential	Based on a CoP of 3 to 4, the carbon savings for heating compared to a gas boiler are expected to be around 0.1 to 0.12 kgCO_2/kWth which is around 60 to 70% saving, resulting in savings on heating bills and reduced reliance on gas. The investment pay offs are approximately ~10 years (compared to non-geothermal). Works best in new buildings and in particular underfloor heating. Existing buildings may require retrofit to reduce thermal losses and to upgrade internal heating systems.
Order of magnitude CAPEX	A borehole to 200m in sedimentary rock would be expected to cost around £10k to drill and install pipework and dispose of waste material. This excludes costs for trenching and testing. Higher costs may occur if abnormal ground conditions are encountered, such as artesian groundwater. CAPEX estimates are around £1,750 to £3,000 per kW of heat capacity [13].
Key risks	The building heating and cooling requirements must be balanced enough to allow sustainable energy delivery. In cases where more energy is used than the ground can sustainably provide, the system can become inefficient to the point of unusable, which is dependent factors such as, building energy loads (and relative balance), thermal capacity of ground, thermal coupling to ground or aquifer, ground connection engineering, heat transfer between ground and heat pump, heat pump type, size and efficiency, system controls up to interface with building [12]. Competent site assessment, design and system implementation are key to preventing failure. Poor installation methods can impact long-term performance by generating leaks within the system. Appropriate testing and documentation are the key to managing this risk.
Testing requirements	Design: ground investigations (soil classification) and thermal response testing. Design must include system sizing based on heating and cooling requirements to ensure energy delivery for life of project, development of testing requirements during installation and interface with building control systems. Construction: GSHPA standards are available for detailed testing requirements including pressure test requirements, flushing, purging and dosing, performance verification for all operation modes, snapshot and seasonal and system optimisation [12].
Environmental impacts	Minimal. However, these systems can require large areas of land. Future development over borefield will be limited to protect the boreholes and piping. These systems can be considered to ‘sterilise’ the ground with regards to future development for the system’s life (typically around 50 years or more).

GSHP: Coaxial Wells or Standing Column Wells

Summary of technology

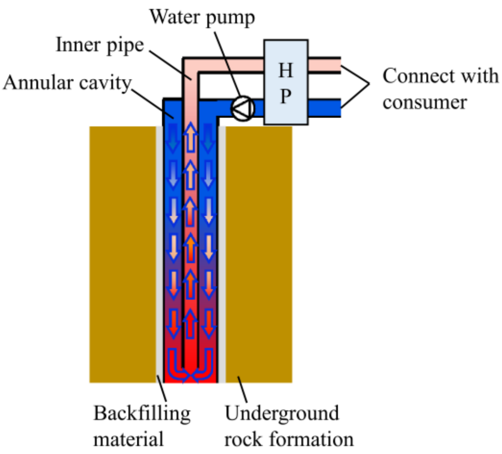
Coaxial wells are formed by installing an inner tubing suspended above the base of the borehole generating an annular space between the borehole casing and the inner tubing. Warm water is abstracted from inside the tubing and from the base of the well and passed through a heat exchanger / heat pump. The cooler water is then passively reinjected back to the well via the annular space, where it is reheated

The outer casing can be sealed, perforated, or even open hole (i.e., no casing). Where perforated or open, circulating fluid is in direct contact with rock-hosted fluids, and therefore has greater regulatory requirements.

To improve system performance, some of the pumped water is sometimes discharged (referred to as 'bleed-off').

The system reduces the amount of boreholes and piping resulting in installation and drilling cost savings.

This type of system is found more often in the United States.



Source: Wang et al (2022) [38]

Typical System Details

Depth range	Up to 500m – deeper coaxial systems are possible (see Section 4.3).
Suitable geology	Fractured low permeability rocks. Whilst these systems can be used in permeable rocks (aquifers), open loop systems are likely to be more cost effective in the latter settings.
Ground T	Up to 40°C but typically around 25 to 35°C at 500m [22].
Application	Hot water, space heating and cooling, potential for district heating.
Scale of energy available	Can be applied in many geological settings, however, importantly they can work in fractured lower permeability rocks where open loop systems are not be possible. Bleeding, which is a process where some of the water within the system is discharged, greatly improves the sustainable energy available from these systems.
COP	CoP values for heating are expected to be at least 3 but may reach up 6 for deeper wells.
Carbon saving potential	Based on a CoP of 3 to 4 the carbon savings for heating compared to a gas boiler are expected to be around 0.1 to 0.14kgCO2/kWth which is around 60 to 80% saving.
Order of magnitude CAPEX	Drilling the borehole and supply and installation of the pipework is dependent on depth. For example, a borehole to a depth of 500m would be in the order of £300k.
Key risks	The building heating and cooling requirements must be balanced enough to allow sustainable energy delivery. In cases where more energy is used than the ground can sustainably provide, the system can become inefficient to the point of unusable, which is dependent factors such as, building energy loads (and relative balance), thermal capacity of ground, thermal coupling to ground or aquifer, ground connection engineering, heat transfer between ground and heat pump, heat pump type, size and efficiency, system controls up to interface with building [12]. Water discharge, known as bleeding (where feasible to do so), is normally required to improve the energy capacity to make these systems effective. Discharge related bleeding may require additional environmental permits.
Testing requirements	Design: ground investigations and including aquifer characteristics, not as extensive as open loop systems. Design must include system sizing based on heating and cooling requirements to ensure energy delivery for life of project, development of testing requirements during installation and interface with building control systems. Testing requirements by the CIBSE memorandum including pressure test requirements, flushing, purging, and dosing, performance verification for all operation modes, snapshot and seasonal and system optimisation[12].
Environmental impacts	Limited (where bleeding is not required). Where bleeding is part of the system, impacts related to water discharge need to be considered as well as the long-term impact of groundwater consumption.

GSHP: Open or Closed Loop Mine Workings

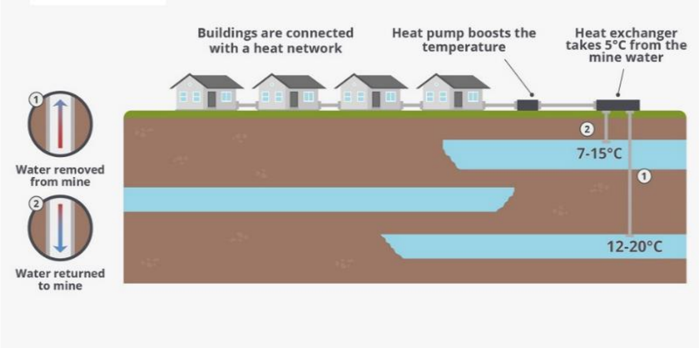
Summary of technology

Mine water energy systems utilise the artificially enhanced permeability within abandoned mine systems for heat exchange. Open and closed loop systems are possible.

Open loop systems utilise boreholes installed into the mine workings to abstract mine water which is then passed through a heat exchanger/heat pump before being returned to the mine workings via another borehole.

Existing mine water abstraction schemes can provide an opportunity for an open loop system.

Closed loop systems would utilise vertical boreholes. Heat is transferred/to from the mine workings to the geothermal fluid within the closed loop.

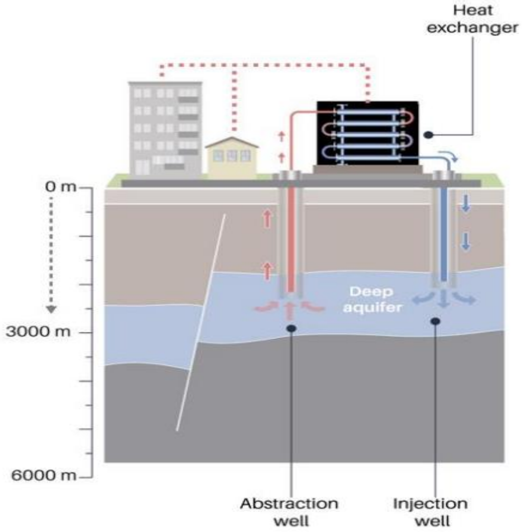


Source: The Coal Authority [9]

Typical System Details

Depth range	The depth is based on depth of the mine workings. In Antrim, NI, the depths of the abandoned mines are unknown. In the area of Dungannon, coal mines are up to 330metres depth and flooded [21].
Suitable geology	Abandoned mine workings (see Figure 7).
Mine water T	Dependent on depth and temperature gradient, expected to be 10 to 20°C in NI, but could be higher.
Application	District heating; space heating and hot water and cooling.
Scale of energy available	Closed loop systems are relatively low capacity (like vertical boreholes). Open loop systems have the potential to have greater capacity due to the high mine water pumping rates that may be possible. Open loop systems may be suitable for district heating but will require a heat pump for high temperature networks and may be more suited to ambient loop heat networks. For an open loop system abstracting at 40 l/s the energy available would be around 800 kWth.
CoP	For heating a CoP in the range 3 to 5 may be possible with cooling expected to be around 6.
Carbon saving potential	Based on a CoP of 3 to 4 the carbon savings for heating compared to a gas boiler are expected to be around 0.1 to 0.12 $kgCO_2$/kWth which is around a 60 to 70% saving.
Order of magnitude CAPEX	Closed loop system costs are likely to be similar to vertical boreholes. For open loop, higher specification materials will be required for groundwater pumps, heat pumps, and pipework due to the water chemistry. Additional costs to mitigate hazards as well as complex hydrogeological modelling to assess thermal interference between wells should be allowed for. Costs may be double those for an aquifer based open loop GSHP system, i.e., up to £1M for a single well doublet.
Key risks	Risks may include (depending on mine / geology conditions), in addition to those described previously. Scaling and corrosion of pumps and pipework due to the mine water chemistry. Thermal interference: Groundwater flow paths within the mine are complex due to the geometry of the mine workings, shafts and adits. Wells need to be positioned to minimise short circuiting. Mine hazards: Abandoned mines are commonly associated with hazards including explosive gases, subsidence, waters elevated in heavy metals and other contaminants. Borehole locations may not actually intersect target mine areas and need to be reinstalled.
Testing requirements	Open loop testing is similar to open loop systems, but more extensive. Additional testing may include gas and settlement monitoring, groundwater quality testing, and monitoring of nearby water courses. More detailed studies are required to evaluate whether mine water flow rate could be supported and identify specific targets for mine water abstraction and injection.
Environmental impacts	Potential for contamination of surface water receptors caused by changes to the mine water system. Changes to the mine hydrogeology through pumping and discharge may mobilise hazardous mine gases that could impact nearby properties (vapour intrusion). Mobilisation of groundwater contamination is possible. Mine water abstraction has the potential to result in settlement/ground disturbances.

4.3 Deep geothermal technologies

Hot Sedimentary Aquifers (Hydrothermal Systems)	
Summary of technology Hot sedimentary aquifers can provide water at higher temperatures but require favourable geological conditions. Deep geothermal systems work in a similar way to an open loop system, utilising a well doublet (i.e., abstraction and discharge boreholes). Abstraction requires a pump (typically an electrical submersible pump). A second pump is often required to deliver the water back into the aquifer (which is normally passively reinjected at the well head). Due to the higher temperatures these systems do not require a heat pump but do require a heat exchanger to transfer heat to buildings or district heating networks.	 Source: UKRI [41]

Typical System Details	
Depth range	500m to 3km. NI sedimentary basin depths extend to around 2.8 km, recorded in the Lower Permian Sandstone Group [23].
Suitable geology	Sherwood Sandstone Group (see Figure 5), Permian Sandstone, Carboniferous Basal Sandstone.
Aquifer temperature	25 to 120ºC, generally geothermal temperature gradient, depth, and fractured of reservoir dependent.
Application	District heat networks (e.g., in Southampton District Energy Scheme) and many other direct heating uses, such as agriculture, dependent on the temperature requirements. Cooling is unlikely to be feasible due to the need for adsorption chillers.
Scale of energy available	Suitable for heating projects situated above hot sedimentary aquifers. Potential sedimentary basins in Northern Ireland include the Larne, Rathlin, Lough Neagh, and the northwest basins). A well doublet (one abstraction borehole and one discharge borehole) abstracting at 20l/s and transferring 30ºC of heat at the heat exchanger (which may be possible at higher temperatures) could provide around 2.4MWth.
CoP/Cost per unit energy	This is highly dependent on the specific project and thermal energy required. A well doublet of two boreholes to 2km, providing a peak delivery temperatures 60-65ºC as direct or 85ºC with high temperature heat pump may cost around £7.5m to drill and at flow rates of 20l/s of 60ºC water and transferring 30ºC heat would provide 2.5 MWth which would equate to around £3,000/kW – currently these are highly bespoke systems.
Carbon saving potential	In systems where heat pumps are not required the carbon savings are potentially significant and only relate to electricity powering the abstraction/circulation pumps. CoP is expected to be close to 15 for heating. With a CoP of 15 the carbon savings are expected to be around 0.16kgCO_2/kWth, 90% of those emitted by a gas boiler providing the equivalent heating.
Order of magnitude CAPEX	Dependent on the number and depth of the boreholes present. Drilling and testing account for most of the cost at £1.6 to £1.8M per km depth. An example from a review of the HSA project at Crewe valued a CAPEX of £15M for two boreholes to around 4km depth to provide around 3MWth [28].

Hot Sedimentary Aquifers (Hydrothermal Systems)	
Key risks	The aquifer permeability is less than anticipated meaning lower flows (and therefore thermal energy) is available than expected. Drilling issues are encountered leading to additional cost and programme delays. In some cases the entire hole can be lost, requiring a redrill, or re-kick-off. Technical maintenance issues such as biofouling and chemical encrustation in the boreholes (at the depths greater than 500m, groundwater will have a high mineral content), corrosion, sand pumping and over- abstraction. [12]
Testing requirements	Surface geophysics such as seismic reflection and magneto-telluric to identify suitable target aquifers. Narrow diameter ‘slim hole’ boreholes should be considered to confirm the conceptual understanding and economic assumptions. However, these boreholes may be expensive, and it may be more cost effective to drill and test the abstraction well without initial investigation boreholes. Extensive test pumping will be required. Detailed modelling of the geothermal reservoir and long-term performance is recommended to determine sustainable abstraction flow rates and appropriate discharge temperature – both of which govern the energy available. Environmental permitting requirements are expected to be similar to open loop systems (see open loop GSHP table). Preliminary surveys include literature reviews, data collection (geological to geophysical), conceptual modelling, numerical modelling, potential resource assessment, seismic risk evaluation, environmental impact assessment, technical and economic feasibility and legal and societal aspects [28].
Environmental impacts	Geothermal fluids can contain dissolved gases, drilling and borehole construction will need to mitigate this risk. There is a risk from thermal breakthrough and reducing flow rates. Thermal breakthrough refers to the process in which ‘thermally spent’ reinjected fluid is unable to thermally recharge prior to re-abstraction, thus acting to reduce the abstraction fluid temperature and overall system efficiency. In the short term, drilling rigs required for deeper well may be large and could produce visual impact (drilling rigs being 40 to 50m in height) and noise impact during the drilling works, which tends to be a 24hour operation to reduce the drilling costs. Noise can affect wildlife and local communities [28]. There is a potential to cause induced seismicity during operation and aquifer testing, in particular where a well doublet is installed to target a fault structure or stimulation is needed (see EGS below). Management of seismic concerns may require careful risk management and community education/engagement.

Enhanced Geothermal System (EGS)

Summary of technology

Enhanced geothermal systems are implemented in hot rocks where there is potential for natural permeable pathways that can be enhanced for circulating geothermal fluids.

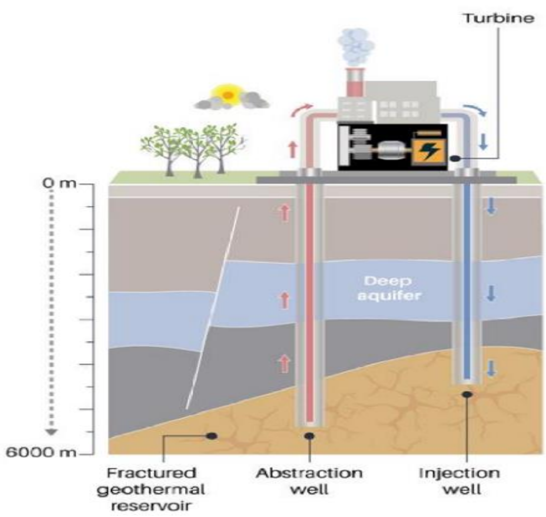
EGS involve drilling an abstraction borehole and a discharge borehole into a fracture/fault system.

The natural fracture networks are then modified through stimulation to enhance their natural permeability and allow geothermal fluid to move from the discharge well to the abstraction well.

The fluid is heated during transit.

A binary plant is required for power production and heat exchanger to transfer heat to a heat network.

Other equipment required includes cooling towers.



Source: UKRI [41]

Typical system details

Depth range	Up to 7 km depth.
Suitable geology	Large igneous intrusions (such as granite) with fault zone or large fracture networks. The granites within NI are poorly understood.
Ground T	Temperature dependent depth but typically for electricity production a temperature of around 150ºC is a minimum requirement for a cost-effective project.
Application	Electricity generation and district heating.
Scale of energy available	Power: A typical system producing steam at 180ºC with flows of 60l/s could produce 3Mwe, for example at the United Downs Deep Geothermal Power (UDDGP) project in Cornwall. Heat: This same project is expected to provide around 15 MWth to a heat network.
Cost / unit energy	Based on a project of similar magnitude to the UDDGP: Power: £6,500/kWe. Heat £1,400/kWth.
Carbon saving potential	Electricity and heat production from deep geothermal energy using a binary power plant produces no carbon emissions at all – the electricity generated is used to power the pumps so is 100% renewable.
Order of magnitude CAPEX	Due to the harder granite rock being drilled, two wells (drilled, cased, cemented, tested, and stimulated) cost in the region of £25M. This would be for one abstraction well to 5km and an injection well to 2.5km. The power plant costs are upwards of £14M, dependent on size.
Key risks	In the short term, financial risks in terms of private sector investments, government funding is required to bridge this gap. Induced seismicity, depending on stress regime, injection pressures/operation strategy and location of geothermal reservoir in relation to settlements and cities.
Testing requirements	Desk based geological research and surface geophysical surveys – if appropriate. Of particular importance is the deep stress regime and some analogues (whether from nearby wells or quarries) need to be located prior to drilling. Deep drilling and deep rock stimulation can be very problematical if the stress regime is not well understood.

Enhanced Geothermal System (EGS)	
Environmental impacts	Environmental Impact Assessment will be needed. In the short term, drilling rigs required for deeper well may be large and could produce visual impact (drilling rigs being 40 to 50m in height) and noise impact during the drilling works, which tends to be a 24hour operation to reduce the drilling costs. Noise can affect wildlife and local communities [28]. Sites need to be chosen where there are no residential dwellings within 200m of the site. Seismic hazard assessments will also need to be undertaken and detailed monitoring networks put in place prior to drilling. Cooling towers can be water-cooled or air-cooled. Water-cooled towers generate vapour which may lead to visual impacts and water supply must be considered. Air-cooled towers may require visual mitigation (as they extend c. 5m above ground level) and may need to be housed in an acoustic-proofed building.

Deep Coaxial Single Well

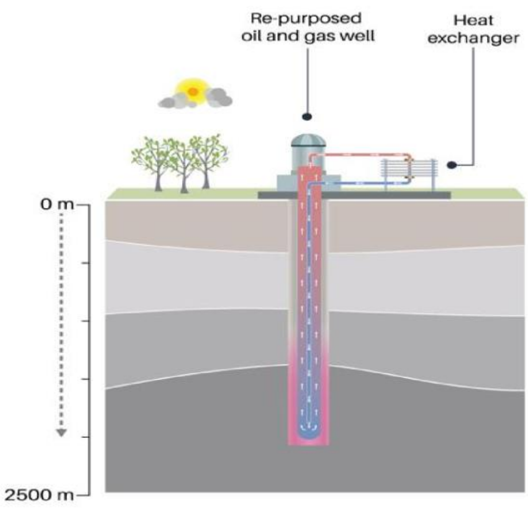
Summary of technology

This system is a deeper version of the standing column well.

These systems are formed by installing an inner tubing suspended above the base of the borehole generating an annular space between the borehole casing and the inner tubing. Warm water is abstracted from inside the tubing and from the base of the well and passed through a heat exchanger / heat pump. The cooler water is then passively reinjected back to the well via the annular space, where it is reheated

The outer casing can be sealed, perforated, or even open hole (i.e., no casing). Where perforated or open, circulating fluid is in direct contact with rock-hosted fluids, and therefore has greater regulatory requirements.

To improve system performance, some of the pumped water is often discharged (referred to as 'bleed-off').

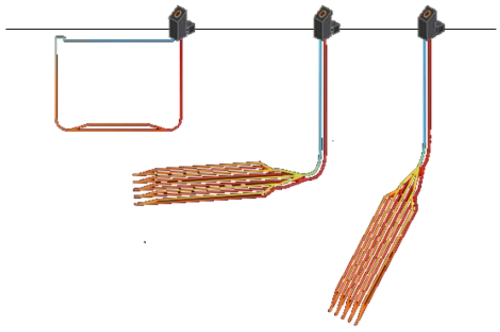


Source: UKRI [41]

Typical System Details

Depth range	Typically, 500 m to 3km.
Suitable geology	Fractured low permeability bedrock. Whilst these systems can be used in permeable rocks (aquifers), open loop systems are likely to be more cost effective in latter settings. There is potential to convert redundant oil and gas boreholes into deep coaxial wells (see Figure 8).
Ground temperature	25 to 100ºC, but typically requires higher geothermal gradient (and therefore higher temperatures) to be economically viable.
Application	Small scale district heating networks, direct use space heating and hot water. Peak delivery temperatures 60-65ºC direct or 85ºC with high temperature heat pump.
Scale of energy available	Typically, a deep coaxial well would be expected to produce around 200 to 400kWth but up to 800kWth with bleeding some of the groundwater.
CoP/Cost per unit energy	This is highly dependent on the specific project and thermal energy required. CoP assumed to be 6 (at a geothermal area like Cornwall it can be between 25 and 40) if a heat pump is required but potentially much higher for direct use. In an area with a favourable geothermal gradient (>30ºC/km), a single well drilled to 3km could produce 400kWth with water at a temperature of around 100ºC and would cost around £5m to drill (this is dependent on rig availability and fuel and steel prices which can be volatile). This would equate to around £12,500/kWth. Operating with bleed of 3l/s, the same system may provide around 800kWth, halving the cost per unit energy to around £6,500/kWth.
Carbon saving potential	Use of low energy electrical submersible pumps means carbon savings can be high and may be around 75% lower than use of a gas boiler for the equivalent heating.
Order of magnitude CAPEX	Dependent on the number and depth of the boreholes present. Drilling and testing account for most of the cost at £1.6 to £1.8M per km depth. Conversion/repurposing of oil and gas wells (prior to plug and abandonment) may be a cost-effective method of developing deep coaxial wells.
Key risks	Water discharge, known as bleeding, is normally required to make these systems cost effective and may require additional environmental permits, or may not be possible. Whilst drilling costs and risks are typically less than more traditional geothermal systems, drilling risks always increase as the target depth increases. So these systems still care more drilling risks than shallow systems. This form of technology is not widely used in the UK and the economic viability has not been proven. Research and additional investigation may be required to prove the viability of these systems at a commercial scale.

Deep Coaxial Single Well	
Testing requirements	In the commissioning of such large projects, often government permissions are needed. Firstly, a preliminary survey is completed, exploratory phase, test drilling and well testing before a project can go fully ahead. Preliminary surveys include literature reviews, data collection (geological to geophysical), conceptual modelling, numerical modelling, potential resource assessment, seismic risk evaluation, environmental impact assessment, technical and economic feasibility, and legal and societal aspects [28].
Environmental impacts	Geothermal fluids can contain dissolved gases, drilling and borehole construction will need to mitigate this risk. In the short term, drilling rigs required for deeper well may be large and could produce visual impact (drilling rigs being 40 to 50m in height) and noise impact during the drilling works, which tends to be a 24hour operation to reduce the drilling costs. Noise can affect wildlife and local communities [28].

Advanced Geothermal System (AGS)	
Summary of technology A very deep form of a multilateral closed loop system that works through conduction of heat from the ground to a working fluid. The loops are formed using advanced drilling techniques to create continuous loops within which the working fluid is circulated. The boreholes are sealed from the adjacent rock using proprietary techniques. Lateral offshoot wells are proposed to be drilled to increase the contact area with the ground. 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 at the surface is used to transfer heat for direct use or power generation.	 Source: Eavor [91]

Typical System Details

Depth range	Proposed to be up to 5 km in depth.
Suitable geology	Sandstone bedrock, but potentially any geology.
Ground temperature	Requires high temperatures, 100 to 200ºC.
Application	Use for heating and electricity generation.
Scale of energy available	Wide range of scales, as the system operated at a range of depths. Eavor (one of the few vendors) claims system use ranges from district heating to electricity generation.
Cost per unit energy	The aims for deep closed loop systems are on the order of £2,000 to £2,500/kWth [30].
Carbon saving potential	This is dependent on the usage, for use in district heating networks the carbon saving potential is significant as 70% of all energy consumption in an EU household comes from space heating [1].
Order of magnitude CAPEX	There is limited data available, drilling method requires advanced drilling technologies and proprietary methods for sealing the boreholes. Estimates on the well cost come to £330 per m for an Eavor loop 2.0 design [33].
Key risks	No functioning projects exist yet, the technology is largely unproven, more pilot projects and research is needed. Significant uncertainty on long term sustainability, mainly due to the potential for very slow conduction/thermal diffusivity leading to low energy production which may result in long term decline in system performance [31]. Complex drilling techniques and significant geological uncertainty at depths approaching 5 km, therefore higher risk of project failure. Limited existing capability in Europe for this type of drilling.
Testing requirements	Desk based geological research to identify suitable target aquifers. Data collection (geological to geophysical), conceptual modelling, numerical modelling, potential resource assessment, seismic risk evaluation, technical and economic feasibility.
Environmental impacts	Environmental Impact Assessment will be needed, although risks appear to be manageable. In the short term, drilling rigs required for deeper well may be large and could produce visual impact (drilling rigs being 40 to 50m in height) and noise impact during the drilling works, which tends to be a 24hour operation to reduce the drilling costs. Noise can affect wildlife and local communities [28].

4.4 Summary Matrix

The summary in Table 3 is based on available geological information for Northern Ireland and for planning purposes only. A detailed feasibility study is required to further evaluate energy capacity and costs, as well as uncertainty and risk. Testing is also required to reduce uncertainty and/or validate the results of any detailed feasibility studies.

Table 3 Summary technology matrix

	Technology	Depth range	Suitable geology	Application	Risk profile	CoP[1] or Cost per unit energy	CAPEX (indicative & for content only)[2]	Carbon savings[3]	Land disturbance	Comment on risk	Testing
Shallow Geothermal	Closed loop horizontal slinky	Up to 5m	Superficial deposits and outcrops	Space heating, hot water and cooling	Low	Heating: 3 to 4 Cooling: 6	£1k - £5k per metre for materials and installation	0.09 to 0.1 kgCO2/kWth (50 to 60% saving)	Moderate to high: horizontal and conveyance piping will be required	Closed loop systems, when properly balanced, and correctly installed are very reliable	Geological tests including thermal response
	Vertical closed loop	Up to 200m, typically spaced on 6 to 8m centres	Superficial and bedrock	Hot water, space heating and cooling, potential for district heating – particular ambient loop	Low	Heating: 3 to 4 Cooling: 6	A borehole to 200m in sedimentary rock would be expected to cost around £10k	0.1 to 0.12 kgCO2/kWth (60 to 70% saving)	Low to moderate: Lots of boreholes but vertical and space efficient	Closed loop systems, when properly balanced, and correctly installed are very reliable	
	Coaxial wells/ standing column wells	200 to 500m	Fractured bedrock		Moderate	Heating: 4	TBC	0.1 to 0.14 kgCO2/kWth (60 to 80% saving)	Low: one single vertical borehole	Relatively unknown and research ongoing. Water discharge disposal is necessary	
	Open loop	Up to 200m	Main Sandstone aquifers and basalts		Moderate	Heating: 3 to 5 Cooling: 6	Around £100k to £500k for a single doublet (depending on the borehole depths)	0.1 to 0.13 kgCO2/kWth (60 to 75% saving)	Low to moderate: one well and abstraction well required for each doublet, minimal piping	Requires initial testing to confirm the aquifer is feasible for use. Once confirmed, the risk profile is similar to a closed loop system	Well drilling and pumping tests
	Mine water (open and closed loop)	Depth varies based on mine workings	Mine workings		Moderate to High	Heating: 3 to 5 Cooling: 6	Around £200k to £1M for a single well doublet (depending on the mine workings depths)	60.1 to 0.12 kgCO2/kWth (60 to 70% saving)	Low to moderate: uses existing mine and requires a heat exchanger	Risks can vary depending on the geology of the abandoned mine. Potential contamination risk. Research ongoing across the UK	

	Technology	Depth range	Suitable geology	Application	Risk profile	CoP[1] or Cost per unit energy	CAPEX (indicative & for content only)[2]	Carbon savings[3]	Land disturbance	Comment on risk	Testing
Deep Geothermal	Hot Sedimentary Aquifers (Conventional Hydrothermal Systems)	500 to 3km depending on location of the Sandstone aquifers	Main Sandstone or limestone aquifers	District heating & cooling and electricity production	High	Around £3,000/kWth	Around £10M for a single well doublet (depending on aquifer depths)	0.16 kgCO2/kWth (90% saving)	Low: one extraction and reinjection well, minimal piping	Potential contamination and technical maintenance	Geophysical surveys, test boreholes (depending on costs), pumping tests
	Deep coaxial single well	1 - 3km	Bedrock		High	Around £6,250/kWth	Around £5M for a single well (depending on depth)	0.14 to 0.15 kgCO2/kWth (80 to 85% saving)	Low: one single vertical borehole	Relatively new technology with few test sites, provides uncertainty on the financial and energy outputs achievable	
	Advanced Geothermal System (AGS)	Up to 5km	Bedrock	District heating and electricity production	High	Around £2,500/kWth	Estimates £330 per m for an example Eavor loop 2.0 design	High	Low: minimal at surface but significant below ground	The technology is largely unproven, more pilot projects and research is needed	
	Enhanced Geothermal System (EGS)	Up to 7km	Fractured igneous intrusions (such as granite)	District heating and electricity production	High	Power: £6,500/kWe Heat £1,400/kWth	Greater than £25M, Power plant costs >£14M (depending on size)	100% Dependent on pump power	Low: one extraction and reinjection well, minimal piping	Seismicity issues still to be resolved. More pilot projects and research is needed	

Notes:

1 – Heating CoP based on output temperature of 65ºC and expected input temperature based on NI geothermal gradient and system depth range

2 - Costs exclude upgrades to buildings, construction of heat networks, heat pumps, heat exchanger and other plant and infrastructure required for a project

3 – Carbon savings are based on comparison to gas boiler proving the equivalent heat energy

5. Policy review

5.1 Introduction

This section summarises a review of geothermal energy regulations and policies from six European countries; Belgium, Denmark, France, Germany, The Netherlands, and Switzerland. The countries were selected based on their geology and similarity of their geothermal prospects to Northern Ireland's. Finland was initially considered in the review but not included as its geology is not comparable to Northern Ireland. Consideration was given to market maturity 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. Where information could not be obtained from these sources, we used our networks to consult with experts in the respective countries.

An effort was made to draw up timelines of how policies and regulation have evolved and shaped the development of geothermal landscape within each country. Where it was not possible to derive a full timeline due to lack of data or because energy policy is devolved, we provide timelines for regional or case studies (e.g., Belgium, Germany) or highlight specific examples of key policy impacts instead (e.g., France, Denmark). The background to this review is included in 0 and a summary of findings is included in Table 5.

Figure 10 highlights the various support scheme options that are utilised by the European countries considered in this review and in Great Britain. Subsidies for geothermal energy are either related to project costs (investment-based schemes) or to the actual generation of energy (heat/power) by a project (production-based schemes).

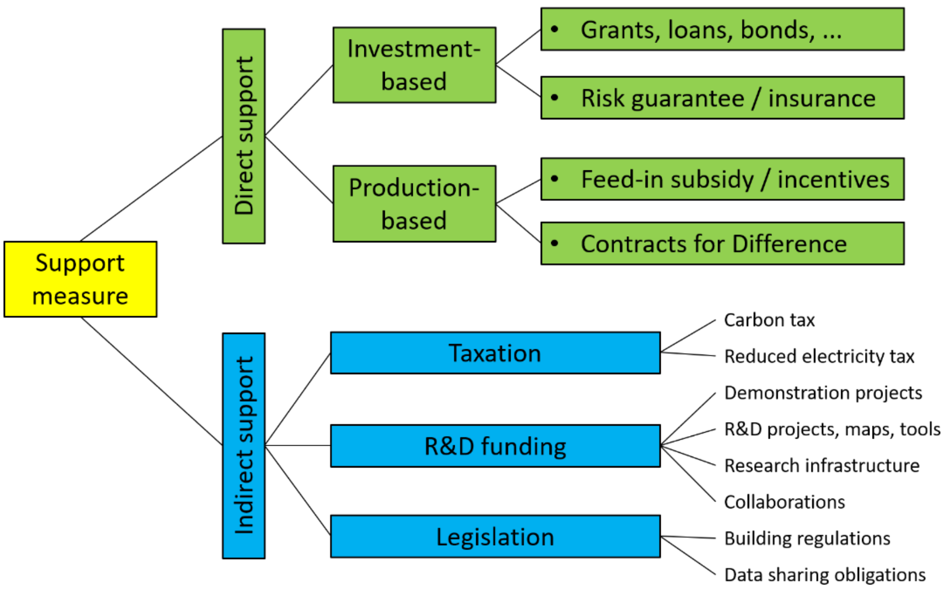


Figure 10 Support measures to develop geothermal energy deployment

5.2 Review of policy mechanisms

In this section, a range of support scheme mechanisms for geothermal energy are introduced and a basic review of advantages and disadvantages for these specific support schemes is presented, including experiences from the reviewed countries.

5.2.1 Direct support

5.2.1.1 Investment bonds, loans and grants

Investment bonds are a method of providing funding for renewable energy investment projects. Bonds enable the investment cost to be shared between current and future generations (Braga in [107]). We have not found any information that suggests that investment bonds are used in the context of geothermal energy support schemes in the reviewed countries.

Loans and grants provide support for developers by covering a proportion of the high upfront capital costs associated with drilling and construction of geothermal energy installations, which can range from several thousand pounds for a domestic GSHP installation to several million pounds for large geothermal heat schemes[84]. They address the gap between first investment and revenues. The main challenge for large-scale geothermal district heating and power generation projects is the time lag between the initial exploration and drilling (1 to 3 years) and the first revenues (after 5 years) from the operational plant.

Grants are more commonly available for shallow geothermal systems, including both domestic level installations (Netherlands, Belgium, Germany) as well as large-scale commercial installations (Belgium, Germany). In these countries, payments tend to be scaled according to system size, unlike the Boiler Upgrade Scheme (BUS) in England and Wales which provides a flat-rate capital grant of £6,000 for all GSHPs up to a size of 45kW. The British scheme was initially set up to pay a grant of £4,000 for all technologies. It was criticised for focussing only on small systems as the cost to the consumer for GSHPs schemes larger than 10 kW becomes too great to make the installation viable even with the subsidy. Even with the higher subsidy, paying the additional capital costs is likely to be a challenge for many consumers, considering that installed prices are in the order of £13,200 for an 8kW GSHP, excluding additional costs related to the heat distribution systems, controls, and ground works for GSHPs. The scheme in England and Wales only became operational on 23 May 2022; thus, it is not yet possible to assess its impact on the market.

Switzerland is the only country in this review that offers grants for DGE, including surface exploration and exploration drilling for geothermal power projects, as well as surface and subsurface exploration and development of direct use geothermal energy projects. As part of its new Energy Strategy 2050, several new measures and a revised incentive system have been in place since the beginning of 2018. These included a raise in geothermal guarantee to 60% of eligible costs (for power projects), new direct financial support of up to 60% for the exploration and development of geothermal resources (heat and power) as well as a revised feed-in tariff (for power projects). The introduction of these updated measures has been reported to have generated great interest and exploration in geothermal energy, in particular for direct use geothermal projects [61].

Loans are not used widely in the reviewed countries, except for Germany where it is the main support mechanism for DGE power and heat projects. The loan is delivered through the government-funded Renewable Energy Incentive Program (KfW Programm Erneuerbare Energien) which also offers cover for unexpected additional drilling costs, e.g., to deepen a well where anticipated yields have not been achieved, thereby combining project financing via a loan with the mitigation of risk [87]. France provides some interest-free eco-loans for SGE, available to individuals utilising geothermal technologies [55].

5.2.1.2 Risk Guarantee//Insurance schemes

Geothermal risk mitigation schemes are highlighted in recent reports as one of the key mechanisms for stimulating the development of deep geothermal schemes, tackling pre-development risks for geothermal energy and leveraging private sector investment [85][86][87][88]. The geological and financial uncertainties over the subsurface conditions and volume of revenue that will be delivered, together with its timeframe, create risks for project developers and investors. As geothermal projects are mainly loan financed, lenders require guarantees that cover any geological incidents that could arise during drilling and operations. Private risk providers are unable to fulfil such risk until the market is fully mature. Hence, Public or Public-Private-Partnerships (PPPs) have been used to fill this gap by mutualising the risk. The French SAF fund, a long-term geothermal risk mitigation measure, was able to leverage €33 for each €1 of public finance for investment in geothermal projects. It provided cover for geothermal drilling and operational risks and has been regarded as a key enabler for the geothermal success in France, including the installation of 500 MW of geothermal capacity over the 35-year run time of the scheme [86].

Different models are used for risk guarantees, including pure grants (e.g., Swiss 2018 – mentioned in the section above), subsidised warranties with low premiums (e.g., SAF Environment, NL geothermal guarantee scheme), hybrid Public-Private scheme - subsidised warranties with low premiums and royalties in case of success (GEODEEP SAS) and others (see [87]). The proportion of costs covered is important for the success of a scheme. At 40 to 60% coverage, the risk remains high for the developer. According to a review of risk mitigation measures by the GEORISK project, funds with 70 to 90% coverage were most successful in European geothermal settings. The report recommends that coverage of at least 60% and premiums in the range of 3 to 7% should be considered to make the policy attractive to developers. The report concludes that long term risk mitigation schemes are only sustainable if many projects are applying [87].

5.2.1.3 Feed-in Tariffs (FiT)

The Feed-in Tariffs are incentive plans that provide users with a range of payments for amounts of power/heat generated from renewable sources. Successful tariffs are typically based on the “cost” to generate electricity/heat and not on its “value”. Implementation and administration of these schemes vary between countries. However, the principle of the FiT subsidy remains the same i.e., it is a fee paid per unit of energy produced, to the generator by energy regulator to allow renewable energy sources to be economically competitive with fossil fuels. For geothermal electricity, the fee is usually allocated by metering and is represented as currency per unit of energy [107]. For heat (which is not a commodity that is metered), an estimation of eligible heat demand is needed for determining the payment amount under the subsidy.

In GB, the non-domestic and domestic Renewable Heat Incentive (RHI) was the principal mechanism to support geothermal heat installations until its closure for new applications in March 2021 and 2022, respectively. Payments were calculated based on the building’s annual heating and hot water demand, the heating system’s Seasonal Coefficient of Performance (to estimate the “renewable” heat component) and the current RHI tariff for the respective renewable technology as determined by the regulator (Ofgem). Unfortunately, in Northern Ireland the RHI scheme caused a governmental scandal which has resulted in a ‘shadow market spoiler effect’ for the whole renewable sector and incentive scheme policymaking[96].

A **Feed-in Premium (FiP)** is a variation of the FiT whereby renewable energy generators are paid a premium in addition to the wholesale price [107]. The Dutch Exploitation subsidy scheme SDE+ (and its recent update SDE++) is an example of a FiP. It is aimed at compensating renewable schemes for the “unprofitable component” of their operation. The subsidy is calculated based on the anticipated cost price of geothermal energy production (€/GJ) (base rate geothermal heat = flat rate), the lower threshold price of non-renewable energy production (base energy price = flat rate) and the average actual market price for heat/electricity during the year (correction rate) – which is recalculated at the end of each year. The subsidy is limited to a maximum amount of production hours (full load hours). The subsidy rates are set according to the level of CO_2 reduction that a technology can achieve and paid based on emission savings (€/tonne CO_2) rather than for renewable energy produced. Figure 11 illustrates the SDE subsidy as a function of the non-renewable energy price. Geothermal heat became eligible for this subsidy in 2012 with a base rate of €10.90/GJ for up to 7,000 full-load hours [64].

Ideally Feed-in Tariffs should be separated out for heating (shallow and deep geothermal) and electricity. Deep geothermal tariffs should consider a Base Tariff with Bonus Tariffs for domestic equipment use, innovation bonus, and a Combined Heat and Power Bonus.

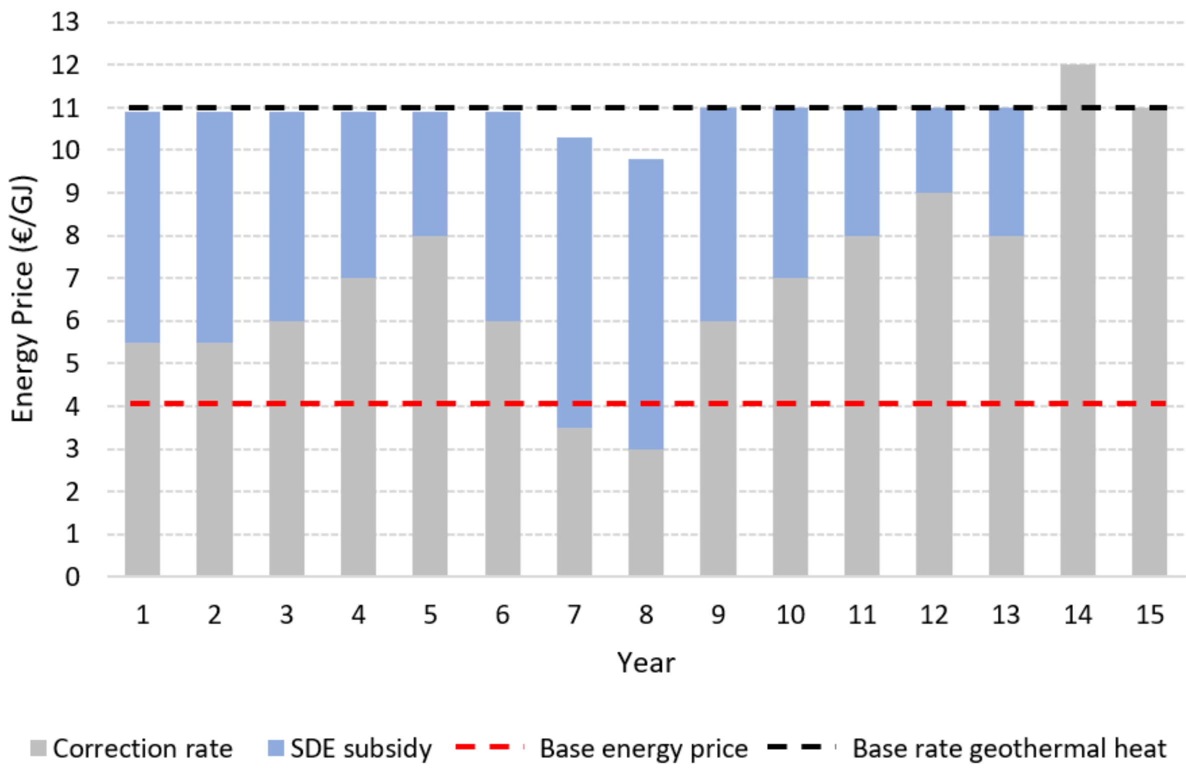


Figure 11 The SDE subsidy as a function of non-renewable energy price, redrawn from [64]

5.2.1.4 Contracts for Difference (CfD)

Contracts for Difference provide a guaranteed price for the electricity that generators sell into the wholesale market, known as a 'strike price'. They are given to power generators from eligible technologies who win a competitive auction. Across Europe, CfDs have fundamental difference in their implementation. In Great Britain a two-way CfD is operated, i.e., when the wholesale price is below the strike price, generators are paid the difference. When it is higher, the generator pays the difference back. Other EU states operate one-way CfD mechanisms where money can only pass from the regulator to the generator. Some countries limit the maximum amount of subsidy that can be paid out under the scheme or the length of time over which it is paid [107]. However, CfDs can only be applied to renewable or low-carbon electricity, rather than heat unless it is regarded as a tradable product/commodity.

Table 4 Comparison of direct policy support mechanisms for geothermal energy development

Mechanism	Advantages	Disadvantages	Comments/Examples
Investment bonds, loans and grants	Upfront capital grants (one off payments) are easy to administer Option to combine loan and risk mitigation (example Germany) Can help reduce large upfront costs for SGE Bridges gap between upfront investment and first returns	Payments must be sufficiently high to attract uptake (example GB) They may fund unsuccessful projects	Germany provides examples of successful loan schemes with risk mitigation Switzerland provides examples of both successful and unsuccessful implementation of grant schemes Switzerland
Insurance/guarantee schemes	A range of mechanisms available, provided in [44] Addresses one of largest challenge for geothermal technologies: high geological and financial risk	Some funds spent on unsuccessful projects Coverage and premiums must be attractive to target users Only sustainable if many projects are applying	Denmark's scheme failed because application and reporting were considered too complex

Mechanism	Advantages	Disadvantages	Comments/Examples
Feed-in Tariffs/Premiums	Rewards successful projects Can be used to reward carbon savings (example NL) Ability to separate heat from electricity, shallow from deep	Method needs to be developed for application to heat (as heat is not metered directly like electricity) Needs continuous administration and annual re-calculation throughout payment period of subsidy	See Netherlands SGE++ tariff for successful example Deep geothermal tariffs should consider a Base Tariff with Bonus Tariffs for domestic equipment use, innovation bonus, and a Combined Heat and Power Bonus
Contracts for Difference	Rewards successful projects Provides a guaranteed revenue for diverse renewable generation over a large market	CfD can only be applied to renewable or low-carbon electricity, rather than heat unless it is regarded as a tradable product/commodity Scheme needs careful management and administration to prevent unfair competition	Geothermal electricity in GB is supported under the GB CfD Scheme, but there is scepticism regarding the extent to which geothermal can be competitive against other supported technologies in its allocated 'lot' which includes offshore wind and Advanced Conversion Technologies (ACT) [41]

5.2.2 Indirect support

Research and Innovation is generally agreed to be a key component in progressing technology development. In the context of geothermal energy, research that improves subsurface knowledge and data availability have been highlighted by a number of countries (Belgium, Germany, Netherlands) as a main contributor for progressing the geothermal sector, together with demonstration and pilot projects. Moreover, transnational collaborations, e.g., through participation in programmes like GEOTHERMICA, have been highlighted as being supportive for knowledge exchange and progression of geothermal developments in the participating countries. GEOTHERMICA is a European Union co-operation project. It is funded with contributions from the participating countries as well as from the European Union Research Fund, Horizon 2020. We have included GEOTHERMICA membership in our review of support mechanisms as GEOTHERMICA (and its successor the CETPartnership – see 5.3. point 12) is available to the UK irrespective of its EU membership status. **Tax incentives** are a method of reducing taxes for renewable energy investors or energy consumers in exchange for specific actions or investments in designated technologies [107]. They are deployed in a number of countries in this review to encourage consumers and businesses to use geothermal technologies. They can take the form of additional tax/carbon levy (e.g., Switzerland, Germany, Denmark) or tax reductions (Belgium). In many countries, environmental and social obligations have been added preferentially to electricity prices. In the UK, they account for about 23% of a domestic electricity bill compared to around 2% for gas. This is viewed by the industry as disincentivising the uptake of heat pumps due to the higher electricity costs among other reasons. Some countries have recently reviewed their electricity prices and reduced (some of) the taxes (e.g., Denmark, Netherlands) to encourage the uptake of heat pumps.

Legislative support can be used to drive wider technology adoption. For example, the UK Climate Change Committee has recommended that from 2025 all new homes be fitted with low carbon heating. Similar measures, including banning installations of fossil fuel fired heating systems in new and retrofitted homes. have recently been introduced in some of the countries reviewed in this study, namely Belgium, Germany and the Netherlands. We have not obtained any statistics that allow an assessment of their impact on the geothermal sector as yet.

Heat Purchase Agreements (HPAs) have not been investigated in this study in any detail. However, they are an important instrument for supporting geothermal projects in less populated and industrialised areas, driving investments in key sectors such as public and residential buildings, industry and horticulture. , to combine heat demand. Examples of geothermal projects structured around long-term HPAs include the Aarhus geothermal project in Denmark as well as most of the 80 geothermal district heating and cooling projects operated in France by municipalities or in Public-Private-Partnership with utilities. In the Netherlands, Letters of Intent have been organised by horticulture producers to access geothermal heating capacity. Power Purchase Agreements (PPAs) (the electricity equivalent) have been key in the UK and Europe in supporting the deployment of renewables in absence of subsidy support.

5.3 Summary and key findings

Table 5 Comparison of regulations and policy mechanism available in the reviewed countries

	Belgium	Denmark	France	Germany	The Netherlands	Switzerland
Data availability						
National Geothermal Resources tool		X	X	X	X	
Regulation/Legal Framework						
Geothermal energy defined as natural resource		X	X	X	X	X
Regulation deep geothermal energy (DGE)						
Licence for exploration	X	X	X	X	X	n/a
License for exploitation	X	X	X	X	X	n/a
Regulation shallow geothermal energy (SGE)						
Licensing//permitting for closed loop	X	X	X	X	X	n/a
Licensing//permitting for open loop	X	X	X	X	X	n/a
National//local register of SGE	X	X	X	X	X	n/a
Sharing obligation for geological data		X	X	X	X	X
Policy						
Investment support, loans and grants	SGE				SGE	SGE/DGE
Feed-in Tariff/Premiums			X	X	X	X
Contracts for Difference	-	-	-	-	-	-
Insurance/guarantee schemes	DGE	DGE	SGE/DG E		DGE	DGE
Research and innovation funding	SGE	DGE	SGE/DG E	SGE/DG E	SGE/DG E	SGE/DGE
incl. access to GEOTHERMICA [76]	X	X	X	X	X	X
Resource assessment tool/GIS/maps		X	X	X	X	X
Tax benefits or penalties; carbon tax etc	X	X		X	X	
Legislative support	X			X	X	

Legend:

X – exists within country

- Not used

SGE – exists for shallow geothermal

	Belgium	Denmark	France	Germany	The Netherlands	Switzerland
DGE – exists for deep geothermal n/a – not investigated as part of this study						

The regulatory and policy mechanisms deployed in the reviewed countries are summarised in Table 5. From the detailed reviews of individual countries – as included in the Appendix- the following commonalities are noted;

1. **Geothermal energy is recognised as a natural resource** in most of the countries that have been reviewed. Where existing legal definitions did not include geothermal energy, legislation was amended to enable regulation and licencing of geothermal energy projects. This was regarded as an important step to create the confidence of financers and project developers in deep geothermal projects (e.g., [81]).

2. **Permitting and licencing** exists in all of the reviewed countries for both deep geothermal and shallow geothermal systems. They are generally regarded to provide confidence to investors and developers as well as to regulators. In the Netherlands, the long-time taken to complete the permitting process has been criticised for putting projects at risk of losing their funding, as investors and suppliers pull out, or because developers cannot meet the application deadline for policy support due to delays in granting of permits. Delays in permitting and licencing are likely to have similar impacts in other countries in this review.

3. Most countries have web-based Geographical Information Systems (GIS) and map viewers, like ThermoGIS in the Netherlands (https://www.thermogis.nl/en), which provide **information and maps of geothermal resources** to help developers and policy makers identify opportunities for deployment of geothermal technologies. The availability of the Bavarian Geothermal Atlas, for example, has been linked with the increase in interest in geothermal energy in Bavaria [41].

4. Four of the countries have **data sharing obligations** whereby it is defined by law or as part of subsidy/licencing conditions that any geological data that are collected as part of geothermal investigations or drilling need to be deposited with a specified public authority, typically the national geological survey. These may be regarded as an important prerequisite for accelerating the development of a geothermal industry, particularly where these data are released for public use or feed into publicly available resource assessment tools/geographical information system (see point 2).

5. **Grants and loans** for geothermal energy technologies are available in all of the countries reviewed here except for Denmark. Grants for SGE are available in the Netherlands, Belgium and Germany but only Belgium and Germany support non-domestic installations. Switzerland is the only country offering grants for DGE. The DGE grants (in Switzerland) 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 DGE for the cost of drilling and plant construction which combines project financing with the mitigation of risk [44].

6. **Government-supported risk insurance/guarantee schemes** are available in all countries reviewed here, except for Germany where risk mitigation measures are part of the government-supported geothermal loan scheme. Generally, government-supported (i.e., public or public-private) schemes are seen as having encouraged geothermal developments in their respective countries, especially at the early development stages when drilling risks, reservoir characteristics and business models are largely unknown. However, in Denmark and Switzerland (prior to a revision of their 2008 policy), risk insurance/guarantee scheme received few or no applications either because application procedures were considered too complex for small district heating operators or because the low percentage of costs covered by the scheme made it unattractive to developers.

7. **Feed-in Tariffs/Premiums** are available in four of the reviewed countries. 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 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.

8. We have not found any details on if or how **Contracts for Difference** (CfD) are used in the context of geothermal energy in the countries reviewed in this study. Generally, CfD can only be applied to renewable or low-carbon electricity rather than heat, unless it is regarded as a tradable product/commodity.

9. **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., Denmark, Germany). Reductions in taxation and levies on electricity have been introduced in some countries (e.g., Denmark, the Netherlands) to reduce operational costs of heat pumps and encourage uptake of this technology.

10. In several countries, support for wider technology adoption is driven through **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.

11. All countries reviewed in this study offer **research support** for geothermal projects. In some countries this includes funding for pilot and demonstration projects (Switzerland), underground laboratories (Switzerland) or large-scale collection of seismic data (Netherlands, Bavaria). 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.

12. All the countries in this review participate in EU funded research projects. They also participate in **GEOTHERMICA** [76] a programme that supports public-public partnerships between EU Member States, Associated and Third Countries. Partners have access to joint programmes initiatives and calls, e.g., focussed on accelerating the piloting, demonstration and validation of geothermal technologies and identifying paths to commercially viable deployment. Participation in the programme requires commitment of some co-funding for involvement in calls. These activities were found to bring several benefits to participating countries including knowledge exchange and transnational collaborations. GEOTHERMICA will finish in 2022. It is succeeded by the Clean Energy Transition Partnership (CETPartnership) which aims to fund projects that develop applicative solutions for the clean energy transition. A number of UK funders have joined the partnership, including Scottish Enterprise and UK Research & Innovation.

6. Northern Ireland Policy

6.1 NI Energy Landscape

The UK has set climate targets by at least 68% reduction in greenhouse gases by 2030 [5] as a first step to achieve net zero greenhouse gas emissions by 2050. The NI Climate Change Act 2022 also aims for net zero by 2050 and has appointed a climate change commissioner [4].

The Energy Strategy for Northern Ireland [1] recognises that geothermal energy can contribute to the decarbonisation of heat and/or cooling. Within the Energy Strategy Action Plan [2] there is one specific geothermal related action (No.16) to support the energy transition; *'to develop and commence delivery of a geothermal demonstrator project'*. Another action (No.15) is relevant; *'Develop and commence delivery of low carbon heat demonstrator projects'*.

For NI, conservation of fuel and power is covered in Part F of the Building Regulations with guidance provided by Technical Booklet F1 (dwellings) and F2 (buildings other than dwellings), both updated in June 2022 [101]. Under the conservation of fuel and power, geothermal is included as an 'energy from renewable source'. NI introduced improvements to energy efficiency standards through Building Regulations in 2012 [100]. In addition, it was announced in 2019 that all new homes built after 2025 in the UK will require low-carbon heating systems.

6.1.1 Northern Ireland Assembly

Geothermal energy is not a new concept to Northern Ireland, it was discussed at the Northern Ireland Assembly as a potential solution to decarbonisation in October 2014. Minutes [102] from the meeting state that;

"A GT Energy document estimates that 81 thermal MW of geothermal energy could be developed by 2020. That represents significantly less than 1% of the stored energy here [In Northern Ireland]. However, 81 thermal MW could equate to approximately 31.5% of the current outstanding renewable heat target of 1,300 thermal GW by 2020. GT Energy believes that this is achievable and is supported by international experience in places such as Paris, where, in the 1970s, over 240 thermal MW were installed over 13 years — an addition of 18 thermal MW a year.

GT Energy has urged the Department of Enterprise, Trade and Investment to install a separate tariff for deep geothermal and to separate it from ground-source heat pumps, which it sees as insufficient to incentivise development. It wants to see a tariff at a suitable level to stimulate the development of the deep geothermal sector. It also wants deep geothermal installations assessed on a case-by-case basis, where proposed projects coincide with an area that is an existing or future gas connection."

Initial investigation stalled shortly after this discussion due to political disagreement, particularly due to the concern around induced seismicity. This highlights the necessity for education and community engagement campaigns to promote deep geothermal projects.

6.1.2 Local Authorities

District councils have a role in reducing fuel poverty, for example, through the delivery of the Affordable Warmth Scheme. Councils' community plans also consider energy matters. Local Councils are outlining renewable energy and low carbon actions within their emerging Local Development Plans (LDPs) which refer to the Northern Ireland Energy Strategy Action Plan [2]. Local councils are also responsible for the determination of the majority of planning applications (local and major) submitted to them. The Department for Infrastructure is responsible for determining regionally significant and 'called in' applications.

6.2 NI regulatory and policy context

6.2.1 Current NI policy and regulation

In regard to policy, investment, and regulation the Northern Ireland Assembly minutes from Oct 2014 [102] note the following;

"It is only through future planning, proper regulation, further consultation and providing proper financial incentives to investors that [geothermal] will become a reality and be delivered."

"[Arlene Foster recognises] that the lack of legislation and corresponding regulatory system may be a potential barrier to the development of deep geothermal energy in Northern Ireland…stable and effective regulation is necessary for investor confidence"

6.2.2 Regulatory approaches

While the Department for the Economy (DfE) leads on energy, the Department of Agriculture, Environment and Rural Affairs (DAERA) is the lead department for climate change. Northern Ireland Environment Agency (NIEA) is an executive agency of DAERA.

In Northern Ireland, if you want to operate an open loop GSHP you need the following authorisation from the NIEA [19];

- a consent to investigate a groundwater source;
- a water abstraction licence;
- a discharge consent.

An authorisation is needed from the Northern Ireland Environment Agency (NIEA) to install a closed loop pump if [19];

- drilling underground causes groundwater from different underground strata to mix together;
- your pump causes changes in groundwater temperature;
- your pump is at risk of causing groundwater pollution.

A streamlined and consolidated regulatory regime will be key for geothermal projects, currently there is no regulation in place for deep geothermal projects and no record of closed loop systems unless they trigger the above authorisation requirements. Geothermal energy is not defined in legislation and there are no mechanisms for drilling under third party lands. With the right regulatory regime geothermal offers an operation lifespan of typically 50 years.

6.3 Geothermal opportunities

A broad range of industries, as well as the residential sector, may benefit from direct use of geothermal heat. The following sections show a number of priority areas which are in line with the 'Building the Geothermal Energy Sector in Northern Ireland' report from 2022 [96];

6.3.1 Twenty-four-hour heat or cooling demands

The heating or cooling of 24-hour buildings (e.g., hospitals, airports, transport hubs, university laboratories, prisons) presents a major decarbonisation challenge.

Geothermal heat is a viable zero carbon alternative to heating/cooling as compared with gas and other fossil fuels. Further detail on case studies can be found in a 2018 publication by BEIS [97]. District heating networks linked to a deep geothermal plant could be utilised for:

- NetZero new build housing and retrofit – A 10 MWth capacity geothermal doublet could provide heat to around 4,500 homes in a district heating network[13].

- Hospitals, Schools, Universities – A 10 MWth capacity project would supply much of the heating requirements for a given site, in particular larger universities and hospitals[13].
- Pools and spas heated by geothermal resource have been used in the UK since Roman times and are gaining popularity.

With an increasing public focus on the carbon impact of the aviation industry there is an opportunity to reduce carbon by incorporating geothermal projects into airports during retrofits or expansions. In addition, airports can consider reducing their carbon use through funding of offsite geothermal projects for other end-users.

6.3.2 Temperature-controlled environments required by pharmaceutical and health care product manufacturers

The Janssen Pharmaceutical plant in Beerse Belgium is an example of how geothermal heat production is feasible at an industrial scale with government support provided [109]. There are also many examples of temperature controlled industries which use GSHPs.

6.3.3 Industrial manufacturing sites

The manufacturing industry is increasingly interested in investigating the potential for geothermal to provide a sustainable, low carbon and cost-effective alternative for heat and cooling, in a move away from gas fired heating.

During stakeholder engagement for the NI energy efficiency research [90] project, it was speculated that the focus for manufacturing companies is on improving their process efficiency and resilience of process equipment in order to maintain and increase product throughput and decrease costs per unit of product.

6.3.4 Agriculture and horticulture

The Independent Strategic Review of the Northern Ireland Agri-Food Sector [94] notes agriculture urgently needs to decarbonise.

There is concern that the government may miss opportunities to invest in new technologies that could unlock agri-food's role in the journey towards net zero. The agri-food sector is well-placed to play a key part not just in renewable energy production, but in the decarbonisation of heat. The review notes that with the right governance, marshalling of technology and investment, circular solutions can be designed which will set NI on the road to decarbonisation of its energy system [94].

The agriculture sector in the Netherlands, France and Italy perfectly demonstrate why geothermal energy is key. Specifically, the Dutch horticulture sector is one of the top global leaders in terms of innovation and trade with international partners being a stable pillar of the Dutch economy [95]. The Dutch horticulture sector geothermal projects represent an installed capacity of over 100 MWth, contributing significantly to lower energy costs [96]. This sector has year-round demand.

6.3.5 NI public sector

In 2020, Arup completed research into energy efficiency policies aiming to inform the development of a new energy strategy for Northern Ireland. During this research it was recorded that the NI building stock comprises nearly 800,000 dwellings (as of April 2018) and 73,000 non-residential buildings, including 4,300 government-owned buildings [90].

Between 2017-2018, government-owned buildings consumed a total of 1,970 GWh [90]. The buildings owned by three departments: DE (Department of Education), DoH (Department of Health) and DFI (Department for Infrastructure) are responsible for most of the energy use. The ten government-owned buildings that consume most energy are shown in Figure 12 and cover more than 25% of the energy used by total government-owned building stock.

There are a number of buildings with high energy use, therefore, this presents a good opportunity to efficiently tackle energy decarbonisation in the government-owned buildings. A key geothermal opportunity is located at Antrim Hospital which is situated above the Sherwood Sandstone aquifer with potential temperatures of 50 – 60°C at around 1km depth [22].

Figure 12 Location of the 10 top energy consumers (government-owned buildings) mapped per local council area, duplicated from [90]

7. Conclusions

This report summarises our review of the geology and geothermal potential across Northern Ireland, both shallow and deep. This includes a review of relevant geothermal technologies describing the characteristics, risks and critical elements of each technology. Geothermal policy and regulations in Belgium, Denmark, France, Germany, The Netherlands and Switzerland were reviewed along with related energy policy and regulatory frameworks in Northern Ireland. Through these reviews, we have identified suggestions of which technologies NI could prioritise to get geothermal developments off the ground along with suggestions for policy and regulatory mechanism and recommendations for further research to realise geothermal developments. Our review of geothermal policy and regulations in other countries has highlighted different regulatory and policy mechanisms for supporting the different geothermal developments. Based on these reviews, and considering the NI energy landscape, we have developed a set of recommendations which are detailed in the following sections and summarised in section 8. A natural next step could be the prioritisation of the recommended actions through engagement with relevant stakeholders in NI. Notably, a previous study undertaken by the BGS involved stakeholders from the UK industry and regulation. The resulting report [84] provides further recommendations for policy and regulatory support for the UK geothermal sector.

Underground Thermal Energy Storage (UTES) was not included in this report. Although closely linked to some of the geothermal technologies reviewed in this report, geological, regulatory and policy requirements for UTES can differ, specifically for high-temperature thermal storage applications.

7.1 Opportunities

From our review of the geology and knowledge of temperature distribution, and as previously outlined in Raine and Reay (2021), we regard the main opportunities for geothermal deployment in Northern Ireland to lie in the use for heating application (rather than power generation), including heating of buildings and greenhouses, as well as for applications in agriculture, industry, and district heating.

The main opportunities for geothermal energy development in Northern Ireland are:

1. **Shallow geothermal resources** including shallow unconsolidated sediments and rocks that have high thermal conductivity as well as shallow high permeability sandstone aquifers; and

2. **Deep geothermal systems** in deep sedimentary aquifers within Permo-Triassic basins.

Further research is needed to better understand opportunities available in other geological settings, including abandoned mines, granites, and unused hydrocarbon wells.

Opportunities for the deployment of **shallow geothermal systems** using ground source heat pumps (GSHP) exist across NI and hence these technologies have potential to make a considerable contribution to the decarbonisation of heating in NI, especially in the residential heating sector which presently largely relies on oil as well as for decarbonising the public estate (hospitals, offices and other government buildings, schools, military bases, prisons).

In new buildings, the uptake of shallow geothermal systems could be encouraged through legislative measures, e.g., prohibiting installation of fossil fuel heating systems in new builds. The retrospective application of GSHP heating/cooling systems to existing housing//building stock is regarded as being more difficult due to the disturbance and costs associated with retrofitting these systems. Initial results from the Department for Business, Energy and Industrial Strategy (BEIS) funded Electrification of Heat Demonstration Project [110] have shown that retrofitting is possible in all types of buildings in the UK [112]. However, incentives will be needed to encourage home/building owners to make the switch to renewable heating. In some of the reviewed countries, technology-specific grants as well as taxation have been used to encourage this transition.

Our energy landscape review has highlighted various opportunities for retrofitting government-owned buildings and the public estate (including schools, hospitals, offices etc.) with geothermal heating (and cooling) systems. Such public sector demonstrators would not only support public sector decarbonisation targets but also make the technology more visible to investors and the wider public. Furthermore, it would provide DfE directly with data on installation and operational costs of these technologies and give a better understanding of the business case and return on investment cycle.

Within the context of raising awareness and improving visibility of geothermal demonstrators, a challenge for geothermal systems – especially GSHPs– is that they cannot be seen at the surface once installation has been completed. This makes it more difficult to raise awareness of the technology, compared to solar and wind installations. It is recommended that extra consideration and effort is given to identifying opportunities and strategies for publicising geothermal demonstrators during and after installation.

Northern Ireland's geology also provides opportunities for the development of **deep geothermal aquifer** (hydrothermal) sources. In the reviewed countries, such developments were found to be most successful where industry//customers with high, all-year round heating or cooling demands are present, such as district heating and cooling (e.g., Germany, France) and horticulture (e.g., Netherlands). In the absence of large heating networks and district heating in Northern Ireland, opportunities for deploying deep geothermal technologies are likely to focus, initially, on applications in horticulture and agriculture or in industry. As opportunities for heat networks are developed through heat network trials and demonstrators [1], geothermal energy from deep aquifers could play an increasingly larger role as a source for district heating.

7.2 Legislation

In most reviewed countries, including Germany, France and the Netherlands, geothermal energy is defined by law as a natural resource. It is regulated through existing legislation, either under the country's mining law and/or (ground)water law, depending on the depth of the resource and whether it involves the abstraction of water. The depth at which different regulations are applied varies between the countries from 100m in Germany to 500m in the Netherlands.

In the UK, geothermal energy is not recognised as a natural resource, and it is not included in mineral legislation. This uncertainty around ownership of heat as well as the lack of a geothermal licensing regime for deep geothermal projects in the UK is regarded by the industry as a potential barrier for deep geothermal investors and developers (alongside the absence of financial incentives). Furthermore, within legislation, definitions for "shallow" and "deep" geothermal vary. For example, the Infrastructure Act 2015 defines deep geothermal as more than 300m below the surface whereas Great Britain's Renewable Heat Incentive (RHI) Scheme Regulation defines it as more than 500m [84].

Geothermal in NI could be supported by a review of legislation to clarify status and ownership of geothermal energy and to support development of a full regulatory framework that enables licencing and permitting of geothermal resources and recognises the difference between "shallow" and "deep" geothermal. This framework should recognise geothermal as a **natural resource** that can be licenced and managed to better mitigate risks to environment, developer, consumer and communities as well as to ensure its sustainable use. Furthermore, the framework should recognise geothermal as a **renewable resource** that is treated differently from fossil or mineral resource, i.e., not associated with royalty payments.

7.3 Regulations

7.3.1 Shallow geothermal energy (SGE)

Water abstraction and injection from open-loop system in NI is regulated under environmental regulations, but it does not consider the heat loads released to / removed from the aquifer. Closed loop systems are largely unregulated. Regulating heat loads is not needed at low levels of deployment, but interference issues may arise in densely populated areas as uptake of GSHP increases. It is hence seen as important that geothermal licencing is considered for open loop systems as well as for large closed-loop systems, Some of the reviewed countries (e.g. France) define licencing requirements based on the depth (>100m) and capacity of schemes (> 230kW). Alternative approaches that consider the annual run time of the scheme (hours/year), in addition to its capacity (kW), are more likely to capture the actual energy loads to the subsurface and hence the environmental impact. Smaller systems/horizontal loops could be defined as permitted development (similar to the French system for installations <100m and <230kW), but registration of their location along with type of system, capacity, and anticipated heating/cooling loads of the scheme should still be considered. Such registers exist in most of the reviewed countries and have the advantage that they provide oversight of how and where the geothermal resource is being used, and hence they enable better resource management. In some countries (e.g. the Netherlands, France), the local registration/permitting system includes obligations to monitor and report return temperatures and water quality (open-loop systems only) to the licencing authority. Such data are essential to inform planning and technology deployment strategies at the local level. Recording the locations of SGE infrastructure is also important for managing and coordinating the increasing demand for subsurface space especially beneath urban centres. Many urban technological infrastructures for transport, utilities, heat and water are located in the subsurface. In the absence of subsurface management systems or records, there is an increasing risk of physical interference between competing uses.

The DfE currently own and monitor all abandoned mines in Northern Ireland, therefore the legacy liability for these assets would need to be considered if any mines were to be repurposed as a geothermal energy resource.

7.3.2 Deep geothermal energy (DGE)

Licencing of deep geothermal systems has been applied in all reviewed countries and is seen as providing confidence to investors and operators by providing clarity on ownership and conditions/duration of use. Licencing also enables regulators to clearly define conditions for use of the resource, including monitoring and reporting requirements, as well as decommissioning responsibilities. In some of the reviewed countries, licences also specify additional conditions such as data sharing obligations or the requirement for public engagement and delivery of social value/benefits to the local community. s.

Further considerations for regulations of SGE and DGE have been identified in Abesser & Walker (2022), including a need for streamlining the regulatory process (e.g., aligning planning, environmental, and health and safety regulations for geothermal applications) [41].

7.4 Policy

Policy incentives are important mechanisms for enabling the dramatic shift in the scale and pace of decarbonisation needed to meet the target of achieving net zero carbon by 2050. Policy measures are intended to reduce key barriers that hold back technology deployment. We have considered a range of policy mechanisms for shallow and deep geothermal technologies.

7.4.1 Shallow geothermal energy (SGE)

For SGE, capital costs associated with the installation of GSHP is the main challenge for many consumers. Installed prices in the order of £13,200 for an 8kW GSHP (excluding additional costs related to the heat distribution systems, controls, and ground works) are far above those of an equivalent fossil fuel heating appliance, like a gas boiler, which cost in the order of £3,000-£4,000. Long payback periods on the initial investment were compounded by the fact that, until recently, gas prices have been considerably lower than those for electricity which carries most of the green levies. This has meant that running costs for GSHPs were only marginally lower than those for a gas boiler. A number of direct and indirect policy measures are available to support SGE as discussed in previous chapter and highlighted in the country reviews (Appendix A).

Direct measures

In our view, the purpose of encouraging installation SGE in Northern Ireland is best achieved through properly managed grant payment schemes. Such grant schemes are the most widely used policy mechanism for SGE in the reviewed countries. They have the advantage that they are easy to administer, especially if provided as a one-off payment.

Experiences in the UK and France demonstrate the importance of offering the right level of support and making it available over long time periods. Tariff imbalances in the GB Renewable Heat Incentive (RHI), for example, initially resulted in falling numbers of GSHP installations in the UK. Similar sensitivity of the heat pump market to policy decisions was observed in France who’s rapidly growing GSHP sector reduced to one tenth of its previous size in 2019 in response to changes in the support framework [40].

Indirect measures

Wider uptake of SGE could be supported by changes to building regulations. In 2019, for example, it was announced that all new homes built after 2025 in the UK will require low-carbon heating systems. Such measures are in place in some of the reviewed countries, but we have not found data that would permit an assessment of their impact on the GSHP//geothermal market. Other indirect measures include special tariffs or tax incentives for GSHPs, such as the reduction of green levies on electricity tariffs or removal of VAT for heat pumps and other energy-saving measures (as currently available in GB). However, some of the proposed policies may not be directly applicable in Northern Ireland and may need adjustment to fit the NI context, including the legislative requirements of the Northern Ireland protocol.

7.4.2 Deep geothermal energy (DGE)

The main challenge for DGE, including large-scale geothermal heating and power generation projects is the time lag between the initial exploration and drilling (1 to 3 years) and the first revenues (after 5 years) from the operational plant. Furthermore, there is a risk associated with subsurface uncertainties of not achieving the flows and temperatures required for the operations of the planned schemes, which presents a barrier for many investors. Hence, policy mechanism for DGE ideally should aim to achieve both: reduce the geological risk and bridge the gap between upfront capital costs and return on investments.

Direct measures

Experience in the reviewed countries has shown that the success of geothermal development is closely linked to the available policies. Government support is required at the beginning of geothermal development in order to encourage and guide financing from the private sector. According to findings from the GEOrisk [113] support mechanisms should be adopted to market maturity. Investment aid in the form of grants and government supported risk mitigations is seen as more appropriate for nascent markets while Feed-in Tariffs together with public risk insurance and public-private partnerships for risk insurance are more appropriate for intermediate and near mature markets [113]. Ideally, government funding should be available to finance the exploratory and pre-feasibility phases of geothermal development (e.g., The Netherlands, France); investors demonstrably take over when the market is more established (e.g., Germany).

Different policy options have been presented in Section 5.2 including:

1. full grants (example Switzerland);
2. feed in tariffs (example Netherlands);
3. loans or combined loan with risk mitigation (example Germany);
4. insurance schemes (example France, Switzerland, Denmark) or subsidised warranties with low premiums (example Netherlands); and
5. a combination of multiple policy mechanisms (example Netherlands, Switzerland).

The advantages and disadvantages of these options were highlighted in Table 5.

EU **grants** have been the main source of finance for the two EGS projects based in Cornwall who secured investments of £9.9 million (Eden Geothermal Project) and up to £10.6 million (United Downs Deep Geothermal Power project) from the European Regional Development Fund (ERDF) [40]. The UK geothermal industry has also been calling for F**eed-in Tariffs** for geothermal, such as the RHI [84]. A recent inquiry by the 1922 BEIS backbench committee [114] concluded that “BEIS could develop a new tariff or Contract for Difference (CfD) to ensure a guaranteed price for .... deep geothermal..., giving confidence to the private sector to invest in such projects”. Geothermal **loan schemes** have not been available in the UK, but the industry has identified a need for **risk-sharing** mechanisms for geothermal projects, e.g., through risk-insurance/warranty schemes [84]. Experience in the reviewed countries and elsewhere [86] has shown that during early market stages, public or public-private-partnership (PPPs) schemes were most successful.

From formal and informal discussions within the UK geothermal industry it appears that there is no consensus regarding which policy measures to prioritise. Furthermore, we understand from discussions with industry that investors are currently quite keen to take on some geological risk; the key issue is that revenues are either very poor or uncertain – or both.

Indirect measures

From our reviews, we have identified a number of indirect measures that have supported developments of DGE markets elsewhere.

1. Development of web-based Geographical Information Systems (GIS) and map viewers, which provide information and maps of geothermal resources to help developers and policy makers to identify opportunities for deployment of geothermal technologies.

    a. In the reviewed countries, development and maintenance of these tools is undertaken by the regional or national geological surveys with funding from national/regional government.

    b. In Northern Ireland, GSNI could take this role of developing such maps using its detailed geological knowledge and data, supported by universities and industry.

2. Setting up sharing obligations for all geological data arising from geothermal investigations or drilling. These obligations can be defined by law or form part of subsidy/licencing conditions.

    a. In countries where such obligations exist, a public authority, typically the national geological survey, is defined as the legal recipient and curator of the data. Data is then released for public use or is used by the national geological survey for developing/updating publicly available resource assessment tools/geographical information systems (see point 1).

3. In Northern Ireland, increasing the availability of geological data for supporting feasibility studies and/or developing national scale maps could accelerate the development of a geothermal industry. Feasibility assessments and maps could initially be delivered through GSNI, supported by the NI geothermal sector. Providing funding to support the geophysical data acquisition, experiments and modelling needed to improve understanding of the geothermal resource.

    a. Subsurface data from seismic campaigns (such as GRAME, SCAN) and drilling are key to improve the understanding of the available resource and reservoir. Funding to support geophysical data acquisition and modelling in target areas could considerably contribute to de-risking geothermal exploration and encourage drilling.

    b. Large scale seismic campaigns could provide a better understanding of structural settings within key geothermal targets, such as the Sherwood Sandstone aquifer.

4. Development of demonstration projects that showcase the technology are important to provide technical, quality assurance, business, and finance models with a focus on the relationship between them and an emphasis on stimulating demand in a way that will mobilise the supply chain. The demonstrator project will not only prove the geothermal resource, but also that the heat can successfully be utilised by a new or existing building or heat network. Data gathered during borehole drilling would be useful for other projects. The pilot project could be used as an educational tool and to quantify the carbon savings and return on investment to encourage other projects.

An option for a suite of funding models for building owners should be considered for those willing and able to fund and/or participate in building retrofits. This may include an effective blend of grants, personal investments, loans, and ‘pay as you save’ models.

Grants should be considered for indirect support measures including administration, promotion, quality assurance, etc.

7.5 Other

An approved set of standards and effective delivery and monitoring mechanisms should be developed to provide confidence in both the geothermal sector and the quality of work subsequently carried out that is robust enough to support funding mechanisms and simple enough to enable wide-spread adoption in the supply chain and understanding in the community.

This report focused on policy and regulation recommendations. Other recommendations are as follows;

- Research and development (R&D):
  - DfE to resource and institutionally support geothermal R&D activity in places where individuals can undertake this research activity [96];
  - The complex geology of Northern Ireland will drive innovation in developing the deep and shallow geothermal sector, and Northern Ireland's reputation.
  - EU initiatives such as GEOTHERMICA have been seen as beneficial to the reviewed countries in building wider research networks and for knowledge exchange. The programme is open to partners worldwide, requiring some ringfencing of funding for participation in geothermal research projects. GEOTHERMICA will finish in 2022. It is succeeded by the Clean Energy Transition Partnership (CETPartnership). A number of UK funders have joined the partnership, including Scottish Enterprise and UK Research & Innovation. We recommend that DfE considers supporting Northern Ireland's participation in the programmes as this could deliver a wide range of research benefits to NI.
- Supply chain:
  - A supply chain can be established relatively quickly using existing skills and experience from the oil and gas sector;
  - Some of these skills may need to be imported but upskilling of the existing workforce should be considered;
  - Overall, the geothermal resource should support the creation of a skilled, coordinated and quality assured supply chain supporting where possible the local economy, of the scale required to match credible, significant, and stable future demand.
- Manufacturing:
  - Steel casing, drill bits etc. are required for the boreholes. This equipment could be produced by the manufacturing industry within Northern Ireland. Heat pumps, exchangers and pipework could be designed and manufactured in Northern Ireland. The manufacturing industry should be consulted to further understand their ability and capacity to develop this equipment.

7.6 Further research and observations

It is recommended that support is considered for the following research and to address the observations included in Table 6.

Table 6 Summary of additional observations and recommendations to support the geothermal industry in NI

Research/Observation	Recommendation
The deep geology and geothermal resource in NI is poorly understood. Most work to date focuses on Sherwood Sandstone Group and is based on a handful of oil and gas boreholes. Limited knowledge of the granite intrusions.	Invest in research to map geothermal potential, map the aquifers in 3D – similar to the work already done by BGS and consider making these publicly available. Research the granites. Complete subsurface data collection to improve subsurface/reservoir understanding. Collate the mine working records and understand condition of the mines. Further investigation work will be required to deduce whether mine water heat in

Research/Observation	Recommendation
	Northern Ireland can offer an economic supply of heat compared to an alternative option such as aquifer heat. Review the oil and gas borehole records and identify those which have potential for conversion to coaxial geothermal energy systems.
Lack of heat demand data.	Map the heat demand for major industry, hospitals, universities etc and overlay on maps showing geothermal potential.
There is currently no financial incentive to develop a geothermal project. There is no Heat Tariff, and the Strike Price is now meaningless. Project revenues only come from wholesale price of power/heat which is low and/or unstable.	Financial models should be developed for shallow geothermal (GSHP), deep geothermal heat and geothermal power projects. Consideration of a feed-in-tariff roadmap which will develop a detailed tariff structure and roadmap for implementation of geothermal projects.
Public understanding in geothermal and confidence in government initiatives are both low. The Renewable Heat Incentive (RHI) scandal, 'fracking' protests and other recent events have indicated low public satisfaction with government initiatives. There is a risk of disengagement in geothermal projects.	A clear and concise community engagement strategy should be developed including educational programmes to increase awareness of the benefits of geothermal and the very low risks to the environment. This will allow trusted groups and individuals interact face to face with the local communities. Particularly focusing on topics such as induced seismicity. An adequate risk management and mitigation plan is needed.
Geothermal power projects need a grid connection which can be expensive to install.	Map the electrical substations and identify those which have capability/capacity for additional geothermal power inputs and compare this to areas of EGS potential.

8. Recommendations

We have made some key observations during this project and have recommended actions that could help to identify and assess the feasibility of geothermal projects and deliver these projects. Our recommendations are summarised below with additional actions in Table 6 that would support the fledgling geothermal industry in NI. These recommendations are based on the current status of the NI geothermal industry and current knowledge of the geothermal resource in NI and should be reviewed regularly as these develop.

8.1 Legislation

We recommend that legislation is reviewed to clarify status and ownership of geothermal energy and that a full regulatory framework is developed that enables licencing and permitting of geothermal resources and recognises the difference between "shallow" and "deep" geothermal. This framework should recognise geothermal as a **natural resource** that can be licenced and managed to better mitigate risks to environment, developer, consumer, and communities as well as to ensure its sustainable use.

8.2 Regulation

8.2.1 Shallow geothermal energy (SGE)

We recommended that geothermal licencing is applied to open-loop GSHP systems and to large closed-loop GSHP systems but that smaller systems/horizontal loops are defined as permitted development which do not require licences or permits if they meet standard conditions. We further recommend a register of all systems that records location, type, capacity, and anticipated heating/cooling loads of the scheme. However, we understand that DfI Planning Group are currently reviewing permitted development rights and depending on the outcome it may be difficult to include SGE detail in a register of systems through the planning system.

8.2.2 Deep geothermal energy (DGE)

A **licencing system** is recommended for the exploration and operation of DGE. Licences should specify ownership and conditions of use (including use of resource and environmental impact, monitoring and reporting requirements and decommissioning responsibilities). In addition, licencing could be used to specify additional conditions related to:

1. requirements for public engagement and demonstration
2. delivering social values and benefits to the local community
3. data sharing obligations.

Licences should be issued separately for exploration and operation and should be time limited. It must be clear who can request the licenses and how, and there should be controls in place to prevent license dealers or monopolisation. License registers should be reviewed annually, and terms and conditions should permit for licenses to be withdrawn, e.g., where licence holders become inactive (i.e., site investigation and exploration are not progressing) or where other licencing conditions are breached.

8.3 Policy

8.3.1 Shallow geothermal energy (SGE)

Direct measures

We recommend that grant schemes are set up for SGE installations of all sizes. To ensure they provide an effective policy mechanism, we recommend that the level of subsidy is set such that it reduces the amelioration period (payback time) to 3-5 years for domestic systems and 5-7 years for commercial systems.

This will require the subsidy to be scaled according to the size of the systems, rather than supplied as a flat rate.

Indirect measures

Indirect measures such as tax relief or changes to building regulations could be considered, but these will have wider legal and political implications that need to be considered. Also, the impact of such measures on the geothermal market will be more difficult to assess, and hence such measures may be more difficult to justify.

8.3.2 Deep geothermal energy (DGE)

Direct measures

Given the observed lack of industry consensus in the UK, we recommend that DfE engages in a consultation process with industry to identify which policy measures to prioritise. The following options could be explored:

1. A combination of a grant scheme with a geothermal insurance scheme (Swiss model): This option would be most closely aligned with current market maturity in Northern Ireland.

2. A combination of feed in tariff and geothermal insurance scheme (Dutch model): This would ensure that only successful projects are rewarded, but historical sensitivities around the RHI (feed in tariff) may need to be considered.

3. A loan scheme with risk sharing options (German model): This option has the advantage of providing financial support while most costs and risks remain with the developer compared to grants where money is paid out by government upfront. The risk sharing options also avoids the need of insurance schemes to attract sufficient uptake to be successful.

Indirect measures

We furthermore recommend that DfE considers implementation of one or more of the following indirect measures:

1. Development of web-based Geographical Information Systems (GIS) and map viewers, which provide information and maps of geothermal resources to help developers and policy makers to identify opportunities for deployment of geothermal technologies.

2. Setting up obligations for all projects that receive government support, subsidies, or licences to share the geological data that arise from geothermal investigations or drilling and deposit these with a supported agency, such as GSNI.

3. Providing funding to support the geophysical data acquisition and improve the characterisation of key geothermal targets, such as the Sherwood Sandstone Group.

4. Support the development of demonstration projects.

Underground Thermal Energy Storage (UTES) is not considered in this report. Although closely linked to geothermal technologies reviewed in this report, 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 (https://www.imperial.ac.uk/earth-science/research/research-groups/ateshac/) and the EU-funded PUSH-IT project (https://www.kwrwater.nl/en/actueel/20-million-euro-grant-for-european-push-it-project/) are being monitored for outputs relating to geological feasibility, and policy and regulations, respectively.

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Country Reviews

Belgium

Policy review

Belgium has small to moderate geothermal potential for direct-use heating and power generation [50]. The geothermal sector is immature compared to that of other countries in this review. However, two deep geothermal projects for district heating are operational at Hainaut (Walloon Region) and Mol (Flemish Region). The respective regional governments have now set up geological risk insurance and guarantee schemes to encourage further deep geothermal developments. Table 7, Table 8 and Table 9 summarise the geological context, regulation, and policies pertinent to the development of geothermal energy in Belgium.

Table 7 Summary of geological context and deployment of geothermal energy in Belgium

	Electricity generation	Direct- use heating	Shallow geothermal
Geothermal potential	Moderate [50]	Small [50]	High
System types	Hydrothermal systems		GSHPs, potential for mine geothermal
Geological target	Fractured and/or karstic carbonates		-
Target depth	1,000 to 6,000 m		-
Geothermal gradient	The geothermal gradient is not well constrained in Belgium		-
Current installed systems/capacity	-	2 deep geothermal projects (17MW)[57] including 3 geothermal heat networks [54]	25,622 GSHPs (339MW) in 2018
Use	-	District heating	Domestic and commercial heating//cooling
Geological context: The largest potential for deep geothermal energy exploitation in Belgium is limited to sedimentary basins to the north (Campine basin) and south (Namur basin) of the Brabant Massif. It is associated with occurrences of thick sequences of Devonian-Carboniferous platform carbonates in these basins [54]. Potential for shallow geothermal systems exists across the country. The presence of numerous coal mines could further provide opportunities for geothermal heating (and cooling) production, but also for deep geothermal reservoir exploration [49].			

Table 8 Regulations and licencing procedure for geothermal systems, Belgium

	Deep geothermal	Shallow geothermal
Regulation	Flemish Decree of 8 May 2009, amended on 1 January 2017 to create the legal basis for exploration and exploitation of geothermal resources in Flanders	Regulation exists for both open- and closed-loop systems, shallow geothermal is defined as the interval within 0 to 500m beneath the surface
Permitting//Licencing	Two-step licencing procedure for geothermal projects > 500m, including exploration and production licenses as well as environmental permit [57]	Licences or permits are required for open- and closed-loop systems
Issuing authority	Flemish government//Energy department	Regional environmental authority
Comments	-	Monitoring is mandatory for open loop systems that extract more than 30,000m^3/year Applications can be completed online via a one-stop-shop (i.e., environmental authority coordinates the overall licencing process)

	Deep geothermal	Shallow geothermal
Regulation: There is currently no national legislation on deep or shallow geothermal energy, but regulation falls with the energy departments of the three regions (Flemish Region or Flanders, Brussels Capital Region, Walloon Region or Wallonia). The table above summarises regulations for geothermal systems in the Flanders Region.		

Table 9 Policy support for geothermal systems in Belgium

Policy mechanism	Deep geothermal//Direct- use heating	Shallow geothermal
Investment support, loans and grants	-	Different financial support available at the regional scale [57] Regional subsidies exist for residential, industrial, and public sector users [55]
Insurance/guarantee schemes	Flanders: geological risk insurance for covering the exploration risk (max €18.7 M, covering 85% of the eligible costs for 7% fee on the insured amount) [54] Wallonia: two-part guarantee schemes formed of (1) regional geothermal guarantee scheme and (2) geothermal compensation scheme provided by the Kyoto Fund [54]	-
/Feed-in Tariffs/Premiums	-	-
Contracts for Difference	Not used	Not used
Research and innovation funding	Regional research and development funding Belgium is a participant in EU project GEOTHERMICA	
Legislative support	Legal obligation to use renewable energy sources for new buildings [57]	
Taxation	National tax reduction for companies who use geothermal energy [55]	
Policy: Geothermal policies vary between regions. Noticeably, Flanders and Wallonia have introduced risk insurance schemes for deep geothermal projects following the development of geothermal heating projects in their respective region.		

Assessment of policy impacts

It was not possible to derive a policy timeline for Belgium, because policy and regulation of geothermal energy is devolved to the regions, and the deep geothermal sector overall is immature. Instead, we have collated a timeline for Flanders, including the Balmatt project in Mol - its first deep geothermal plant which serves as a pilot and demonstration site.

Figure 13, highlights a number of important aspects that have contributed to the success of the project, including

1. Amendments to subsurface regulation/laws to provide legal basis for exploration and exploitation of geothermal resources in the deep subsurface of Flanders

2. Stakeholder-focussed approach involving researchers, regional businesses, and local stakeholders/municipalities as well as the regional government to develop a clear strategy (roadmap) for developing the project (and geothermal energy) as part of the regional energy transition.

3. Financial support from the regional government for drilling the first well.

Consistent stakeholder engagement and realisation of local benefits at Mol are considered a key reason for the success of the Balmatt project. The importance of engagement is highlighted by the contrast in experience in Mons in the neighbouring Walloon region where a similar geothermal project [69] had to be cancelled because of local opposition[70]. Another point to note is that, as part of integrating the delivering deep geothermal in the regional energy transition, the Flemish government has now introduced a risk insurance scheme for deep geothermal projects in order to encourage further projects. Since introduction of the scheme, other projects have started exploring potential for geothermal heat exploitation in the area (Laenen 2018, pers comm).

In addition, Bos & Laenen [47] highlight the importance of the Balmatt project in reducing the deep drilling risk by proving the geothermal resource in the target aquifer for heat and power generation, and in providing critical information on drilling costs to support the development of business cases for other deep geothermal energy projects in the area.

Denmark

Policy review

Denmark has moderate potential for geothermal electricity generation and direct use heating [50][58]. With one geothermal heating plant in operation since 1981 and two others temporarily closed due to operational problems, the geothermal sector remains immature. Table 10, Table 11 and Table 12 summarise the geological context, regulation, and policies pertinent to the development of geothermal energy in Denmark.

Table 10 Summary of geological context and deployment of geothermal energy in Denmark

	Electricity generation	Direct- use heating	Shallow geothermal
Geothermal potential	Moderate[50]	Moderate[50][58]	High
System types	Hydrothermal system		Ground Source heat pumps (open-loop, closed loop); Underground thermal energy storage (UTES)
Geological target	Porous, fractured sandstone		unconsolidated, shallow geology and shallow aquifer systems of variable thickness//depth
Target depth	800m to 3,000m [62]		-
Geothermal gradient	25 to 30°C/km [62]		-
Current installed systems/capacity	-	1 operational geothermal heating plant (2 other plant closed due to operational problems)	57,000 heat pumps (undifferentiated) in 2021. Only a few hundred closed-loop and < 40 open-loop GSHPs. One BTES and 5 district heating networks based on closed-loop BHE [62]
Use	-	District heating	Domestic and commercial heating, district heating
Geological context: Deep geothermal potential in Denmark occurs in two deep sedimentary basins: the Danish Basin (DB) and the North German Basin (NGB). Five important geothermal reservoirs have been defined based on their stratigraphical and spatial extent. The reservoirs comprise several sandstone layers, deposited at different intervals between the Lower Triassic and the Lower Jurassic periods [72]. A number of other formations exists which may contain potential geothermal aquifers of local extent, but these are not currently being exploited [62]. Shallow geothermal energy potential exists across Denmark. The shallow geology is dominated by soft sediments of glacial sand and clay deposits of variable thickness and characterized by a variable depth to the groundwater table [62].			

Table 11 Regulations and licencing procedure for geothermal systems in Denmark

	Deep geothermal	Shallow geothermal
Regulation	Resource regulated under the underground act, based on the framework for oil and gas, separate regulation for environmental impacts[1]	Shallow geothermal energy (SGE) is regulated pursuant to the Danish Environmental Protection Act, the Ground Source Heating Act[62]
Permitting//Licencing	developers are required to apply for an exploration licence which is valid for 6 years development which can later be extended to a 30-year production licence [Berg Lorenzen (2022, pers comm)]	Licences are required for all forms of SGE [55] Issued free of charge, without time limit
Issuing authority	Danish Energy Agency	Municipalities
Comments	Competing application for same licences area are awarded on merit to what is judged to be the better project in terms of overall ambition, including new data collection and overall capacity of the plant [Berg Lorenzen (2022, pers comm)]	Regulation of open-loop GSHPs comes under the Act on "Heat extraction plants and groundwater cooling", requires a detailed investigation and numerical modelling of the aquifer[52] Regulations include restrictions on injection temperatures for both, open and closed loop systems as well as mandatory groundwater temperature monitoring for Aquifer thermal energy storage systems[56]
Regulation: Geothermal Energy in Denmark is considered a natural resource. Deep geothermal energy (DGE) developments are regulated under the underground act, which initially only included oil and gas and rock salt but recently has been extended to include geothermal. Licences are required for shallow geothermal energy (SGE) as outlined above.		

Table 12 Policy support for geothermal systems in Denmark

Policy mechanism	Deep//Direct- use heating	Shallow geothermal
Investment support, loans and grants	-	-
Insurance/guarantee schemes	A £10 Million guarantee scheme to insure against economic risk associated with geothermal drilling projects[52] [Berg Lorenzen (2022, pers comm)] *	-
/Feed-in Tariffs/Premiums	-	-
Contracts for Difference	Not used	Not used
Green Certificates//Renewable obligations certificates	-	-
Research and innovation funding	Government has financed several research projects that focus on the implementation of deep geothermal for district heating networks, including [62] WebGIS geothermal portal Develop business models for large scale use of geothermal energy Evaluation of geothermal potential from legacy seismic data Participant in EU project GEOTHERMICA	-
Legislative support	Licences for geothermal resources include an obligation for all geological data that are acquired during exploration and drilling to be deposited with the national geological survey (GEUS). Information is kept confidential for the first five years but then becomes	-

Policy mechanism	Deep//Direct- use heating	Shallow geothermal
	publicly available to support geothermal exploration of the area	
Taxation	High taxes are applied to fossil fuels to incentivise uptake of green energy technologies [52]	Reduction in taxation on electricity for heating to almost zero in 2021 to encourage uptake of heat pumps [80]
Comments	* The guarantee scheme has not received any applications so far [Berg Lorenzen (2022, pers comm)] Availability of long-term heat service agreements is seen as an essential prerequisite to encourage investment in geothermal.	-
Policy: There is no direct government funding for geothermal but high taxes are applied to fossil fuels to incentivise uptake of green energy technologies [52]. Despite a general lack of incentives for geothermal technology, Innargi has announced a large-scale geothermal development in Aarhus to provide heating for 300,000 inhabitants. Furthermore, Denmark last year reduced taxation on electricity for heating to almost zero to address the imbalance between electricity and gas prices [80] and encourage uptake of heat pumps. Geothermal energy technologies are also expected to benefit from price regulation under the Heat Supply Act. A summary of policy support and research funding for geothermal technologies in Denmark is provided above.		

Assessment of policy impacts

It was not possible to derive a policy timeline for Denmark, because the geothermal sector in Denmark is immature with no direct government funding in form of grants or subsidies available at present. However, the Danish Government has recently (2018/19) established a £10 million risk guarantee scheme that enables licence holders to insure against economic risk associated with geothermal drilling. They appointed an expert committee to evaluate the applications. To date, the scheme has not received any applications despite a rising interest in geothermal developments in the country. The securities offered by the scheme are considered adequate. The lack of uptake is attributed to the application procedure and documentation requirements which are seen as too complicated for the target applicants – usually small district heating companies with little knowledge of geothermal technologies (Berg Lorenzen, 2022, pers comm).

Despite lack of direct subsidies for geothermal heat developments, Innargi has announced a large-scale geothermal development in Aarhus to provide heating for 300,000 inhabitants. The £200 million project is planning to drill 17 wells up to a depth of 2 km. Recognising the limited geothermal expertise and investment capacity of district heating providers (the main geothermal end-users for deep geothermal heat in Denmark), Innargi will use its own funds to build, own and operate the geothermal plant and will then sell the heat to district heating companies in the area. To secure its investment, Innargi has signed a 30-year heat service agreement. Such agreements together with a reliable heat customer base (i.e., district heating companies) are key prerequisites for Innargi' s business model to succeed (Berg Lorenzen, 2022, pers comm). Furthermore, by deploying oil field development strategy, i.e., drilling lots of wells, the company is aiming to mitigate the geological risk associated with drilling into an unknown reservoir.

France

Policy review

France has high potential for geothermal electricity generation and direct-use heating [50]. It is one of the pioneering countries in the development of deep geothermal heating with the development of the Paris Basin hydrothermal aquifer which still presents the highest density of low-enthalpy geothermal energy operations in the world. Table 13, Table 14 and Table 15 summarise the geological context, regulation, and policies pertinent to the development of geothermal energy in France.

Table 13 Summary of geological context and deployment of geothermal energy in France

	Electricity generation	Direct- use heating	Shallow geothermal
Geothermal potential	High [50]	High [50][58]	High
System types	Hydrothermal systems Enhanced Geothermal System		GSHPs, ATES
Geological target	Porous, fractured sandstone and fractured limestone fractured granite		Unconsolidated, shallow geology and shallow aquifer systems of variable thickness//depth
Target depth	600m to 2,000 m		-
Geothermal gradient	30°C/km Some areas have pronounced temperature anomalies (Temperatures of >50°C and >90°C at 1km and 2km depth, respectively) [50]		-
Current installed systems/capacity	1 operational EGS plant (Soultz-sous-Forêts, 1.7 MW) and several new EGS sites under development [44]	46 geothermal heating projects (600 MW) and 80 geothermal district heating systems [77]	c. 175,000 heat pumps (2020) [77] 2,000 MW of installed heating and cooling capacity [44]
Use	Electricity generation, Combined Heat & Power	District heating, some leisure/fish farming//agricultural use	Domestic and commercial heating and cooling
Geological context: Deep geothermal targets in France are located mainly within deep sedimentary basins, including the Paris Basin in central France and the Aquitaine Basin in southwest France. The hydrothermal aquifers within these basins mainly consist of sandstones and limestones of Cretaceous and Jurassic age. The resources are found at depths between 600 and 2,000 m. Outside of France's Overseas Departments, geothermal power generation potential is limited to use of EGS systems in areas of high geothermal anomaly, e.g., the Upper Graben (in Alsace).			

Table 14 Regulations and licencing procedure for geothermal systems in France

	Deep geothermal	Shallow geothermal
Regulation	French Mining Code	French Mining Code applies to systems > 100m deep [44]
Permitting//Licencing	Exploration and exploitation licences are required for all systems, issued by different authorities, depending on size of the systems [44]	Horizontal systems are not subject to regulation Systems < 100m and < 230kW are permitted developments but need to be registered [55][56] Other open- and closed-loop systems must obtain a licence (free of charge) [56]
Issuing authority	Regional authorities (< 20MW) Ministry of Environment (>20MW)	Regional authority (DREAL)
Comments	-	Licences define a set of requirements including annual inspections and reporting of productions

	Deep geothermal	Shallow geothermal
		rates and output temperatures as well as environmental monitoring
Regulation: Geothermal energy is recognised as natural resource in France. The resource is owned by the state. Regulations and licencing procedures are in place, both for deep and for shallow geothermal systems, although exemption apply for horizontal GSHP systems and for permitted developments (i.e., GSHPs that fall within a predefined capacity/depths range). The main regulations for geothermal systems in France are summarised above.		

Table 15 Policy support for geothermal systems in France

Policy mechanism	Deep Geothermal	Shallow geothermal
Investment support, loans, and grants	Renewable Heat Fund (€307 million in 2019, c. 10% for geothermal energy) [66] supporting successful geothermal developments for housing, tertiary, industry, and agriculture*	Interest-free eco-loans available to individuals utilising geothermal technologies [55]
Insurance/guarantee schemes	GEODEEP SAS is a fund for EGS systems, risk mitigation based on public/private financing covering exploration drilling and 10 years of operation [66] SAF Environment direct use geothermal risk mitigation fund, public/private financing, grants & subscription fee	Aquapac is a risk mitigation fund based on public/private financing for open-loop (groundwater) heat pump projects with a heat capacity > 30kW and installations depth < 100m [55]
Feed-in Tariffs/Premiums	Feed-in Tariffs for electricity have ceased for new developments in the mainland but can still be accessed by existing geothermal developments and those in French overseas territories [77]	-
Contracts for Difference	Not used	Not used
Research and innovation funding	Investments for the Future programme funds research and development into deep geothermal Géodénergies - an Institute of Excellence for the use of the underground in the energy transition was created in July 2015 Participant in EU project GEOTHERMICA	-
Legislative support	-	-
Taxation	-	-
Comments	* the Renewable Heat Fund also applies to large scale SGE	French policy is focussed on supporting SGE for collective housing. Support for individual homeowners/housing deployment has been reduced [44]. This change in policy has been attributed to the decline in the GSHP market [50].
Policy: A range of policy mechanisms are available for geothermal technologies in France. Most noticeable are the two risk guarantee funds - GEODEEP SAS for deep geothermal and Aquapac for shallow. France is the only county in our review that offers risk guarantees for shallow geothermal systems. A summary of the available policy mechanism is given above.		

Assessment of policy impacts

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 1980's. Since then, geothermal development has broadened to include shallow geothermal energy (SGE) 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 undoubtably linked to consistent technology support (since 1980s) and city scale deployment (right market conditions) to existing district heat networks (e.g., Paris Basin). A detailed account of how risk mitigation measures, including the long-term scheme managed by the SAF Environment subsidiary of the Caisse des Dépôts et Consignations that was available from 1982 – 2015, have contributed to geothermal success in France is given in Boissavy [43].The Fund received initial funding from the state, which was topped up by payments from beneficiaries (3% of the cost of the installations guaranteed) and by financial income arising from investing available cash. Over its life time, 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 investments were covered by other income for period of 25 years [43].

Even today, France occupies a leading role in risk mitigation subsidies. It is the only country in this review to offer risk mitigation funds for both shallow (>30kW) and deep systems, including insurance for the operational stage of deep geothermal projects. Unfortunately, we have not obtained sufficient data or information to derive a policy timeline or to assess the impact of these insurance schemes on the geothermal market.

France also held a leading role in the deployment of shallow geothermal energy (SGE) technologies. The initial expansion of the sector was largely attributed to the policy support from EDF (French Electricity Board) and Ademe (French Environment and Energy Management Agency) and the engagement of small-scale manufacturing industry [98]. However, despite its strong assets and the initial progress made by the sector overall, numbers declined for SGE from new annual installations of 19,430 in 2008 to 2,582 in 2019 [78]. The decline is attributed to the government's decision to suddenly reduce the support framework for SGE without prior consultation with the industry [50]. The dramatic reduction in deployment of SGE highlights the market sensitivity to policy decisions even in established markets.

Germany

Policy review

Germany has very high potential for geothermal electricity generation and high potential for direct use heating [50][58]. Deep geothermal developments have focussed on the Molasse Basin in southern Germany, specifically on the area around Munich in Bavaria which remains one of Europe's best showcases for large-scale development of deep geothermal energy (DGE) ([41] p. 26). Table 16, Table 17 and Table 18 summarise the geological context, regulation, and policies pertinent to the development of geothermal energy in Germany.

Table 16 Summary of geological context and deployment of geothermal energy in Germany

	Electricity generation	Direct- use heating	Shallow geothermal
Geothermal potential	Very high [50][58]	High [50][58]	High
System types	Hydrothermal system Enhanced Geothermal System		GSHP, UTES, mine geothermal
Geological target	Fractured and/or karstic carbonates		Unconsolidated, shallow geology and shallow aquifer systems of variable thickness//depth; abandoned mines
Target depth	500m to 6,000m		-
Geothermal gradient	Average 30°C/km but some areas with pronounced temperature anomalies (Temperatures of >50°C and >90°C at 1km and 2km depth, respectively) [50]		-
Current installed systems/capacity	38 operating geothermal plants 9 of which also produce electricity Total heating capacity: 350 MW Total electricity capacity: 47 MW [83] In addition, there are 190 geothermal installations for direct use (in 2018) including district heating and thermal spas, and one geothermal greenhouse in Bavaria [83]		c. 440,000 GSHPs (in 2020)[83]
Use	Combined heating and power generation	District heating, thermal spas, space heating	Space heating, commercial heating and cooling
Geological context: Germany has three regions that are suited for geothermal energy use: the North German Basin, the Upper Rhine Graben, and the South German Molasse Basin. The Molasses Basin (mainly in Bavaria) is currently the most widely used geothermal aquifer, exploited extensively for both geothermal power and district heating. The target aquifer is a fractured karstic limestone of Jurassic age. Potential for geothermal heat pumps exists in all parts of Germany.			

Table 17 Regulations and licencing procedure for geothermal systems in Germany

	Deep geothermal	Shallow geothermal
Regulation	Federal Mining Act and Federal Water Act as well as environmental and energy legislation [73]	Regulation exists for all shallow geothermal systems in Germany with an expected yield > 0.2MW and where boreholes are drilled to depth < 100m [55]; Federal Water Act (WHG) applies to all systems impacting on//in contact with groundwater [73]; Federal Mining Act applies to all systems > 100m
Permitting//Licencing	Licences required for exploration and production of geothermal energy at a depth of 500m below the surface [46]	Licencing/permitting is mandatory for open loop systems and closed loop systems [73]

	Deep geothermal	Shallow geothermal
	Conversion of successful exploration license into exploitation license is possible [46]	Each federal state has its own regional procedure of licencing, regulated by their regional rules/laws.
Issuing authority	State Ministry for Economy	In many federal states, application is coordinated by the water authority who is processing the applications, conferring with other authorities where necessary [73]
Regulations: Geothermal energy is recognised as a natural resource in Germany. The resource is owned by the state, but exploration and exploitation activities generally can only be undertaken by the landowner. National regulations apply to geothermal energy, but licencing procedures are defined at the Länder (federal state) level. Above is a general overview of regulations and licencing procedures in Germany.		

Table 18 Policy support for geothermal systems in Germany

Policy mechanism	Deep//Direct- use heating	Deep//Power generation	Shallow geothermal
Investment support, loans, and grants	KfW-Programm Erneuerbare Energien: Plant: €200/kW capacity up to €2Mill Drilling: €375/m to €750/m drilled depth (up to a total of €2.5Mill per well) Unexpected additional drilling costs: 50% up to €5Mill per project[3]	KfW-Programm Erneuerbare Energien: Plant: up to €2Mill Drilling: €375/m to €500/m drilled depth (up to a total of €975k per well//€3.9Mill per project) Unexpected additional drilling costs: 50% up to €5Mill per project	Market incentive programme (MAP) funds new heating technology with a minimum grant for GSHPs of €4000 to >€7000 [80] €80/kW capacity for large heat pumps
Insurance/guarantee schemes	Some risk coverage included in the national KfW programme		-
Feed-in Tariffs/Premiums	-	Subsidy of €0.25 to 0.30/kWh for geothermal electricity [80]	-
Contracts for Difference	Not used	Not used	Not used
Research and innovation funding	Government- funded web-based open access Information System (GeotIS) 147 government-funded geothermal research projects (by 2020) 7th Energy Research Programme (€7 mill) focussing on demonstration projects; cost reduction, UTES, development of geological database for geothermal uses [83] Participant in EU project GEOTHERMICA		-
Legislative support	Renewable Heat Act obliges new builds to use renewable energy [80]		
Taxation	CO_2 tax came into effect in January 2021 [83]		-
Policy: Germany has several national policy mechanisms, including upfront grants for heat pumps and a feed-in tariff for geothermal power generation, in addition to research & innovation funding. Additional incentives often exist at the Länder level.			

Assessment of policy impacts

Our assessment focused on developments in Bavaria where most of Germany's deep geothermal activities have taken place to date. In addition to favourable geology provided by the Molasse Basin (which hosts the deep geothermal aquifer beneath Munich), the success of DGE in Bavaria has been linked to three supporting factors: (1) the availability of a geothermal atlas, (2) long-term government support, and (3) availability of research funding to support the geophysical data acquisition, experiments and modelling needed to improve understanding of the geothermal resource [41].

A general timeline of geothermal development in Bavaria is presented in Figure 14. The figure highlights that financial support has been available throughout the market development phase of geothermal project. Continuous collection of subsurface data from seismic campaigns and drilling has considerably improved the understanding of the resource and reservoir. Most noticeable is the €8 million research project called GRAME that was set up to support geophysical data acquisition, experiments and modelling to improve understanding of the geothermal resource [41]. There has been a steady increase in geothermal installations, but a marked rise followed the introduction of first 2D seismic data for geothermal.

The main support mechanism for deep geothermal power and heat projects is the government-funded Renewable Energy Incentive Program (KfW Programm Erneuerbare Energien). It offers a loan for the cost of drilling and plant construction based on capacity of the plant and number and depths of the wells (up to a maximum amount available per project).

A risk insurance scheme for geothermal drilling was set up in 2003 with a private insurance company acting as the direct insurer. The scheme was intended to cover a minimum of 5 geothermal wells but was withdrawn by the company after the failure of the first two geothermal wells covered by the scheme. In 2009, a new scheme was announced by the government-owned bank Kreditanstalt für Wiederaufbau (KfW) and a private insurance company. Although regarded as a sustainable programme in principle, “manual errors” in the way it was operated meant that it was practically “unusable”, mainly because it did not match the cash flow cycle of a geothermal project (Pletl 2021, pers comm). Since 2013, extra costs arising from unexpected drilling (e.g., for deepening a well where yields have not been achieved) can be covered as part of the Renewable Energy Incentive Program (administered by KfW) which combines project financing via a loan with the mitigation of risk [44].

The Netherlands

Policy review

The Netherlands has high potential for geothermal electricity generation and for direct-use heating. However, a policy decision has been made to focus geothermal developments on supplying heating for horticulture, district heating and industry rather than on power production. Table 19, Table 20 and Table 21 summarise the geological context, regulation, and policies pertinent to the development of geothermal energy in the Netherlands.

Table 19 Summary of geological context and deployment of geothermal energy in the Netherlands

	Electricity generation	Direct- use heating	Shallow geothermal
Geothermal potential	High [50]	High [50][58]	High
System types	Hydrothermal		Underground thermal energy storage, Ground Source heat pumps (open-loop, closed loop)
Geological target	Porous, fractured sandstone Fractured and/or karstic carbonates		Unconsolidated, shallow geology and shallow aquifer systems
Target depth	500 to 3,000m [63]		-
Geothermal gradient	Average 31°C/km [45]		-
Current installed systems/capacity	-	28 operational geothermal systems [48]	67,820 GSHP systems (in 2018) including UTES [75]
Use	-	Heating for horticulture, district heating and industry [67]	Domestic and commercial heating & cooling
Comment	Political decision to focus on geothermal heating	-	-
Geological context: Deep geothermal energy prospects in the Netherlands are concentrated in deep sedimentary basins, mainly in Sandstone units of Permo-Triassic, Jurassic/Cretaceous and Tertiary age. In addition, limestones of Lower Carboniferous (Dinantian) age have been proven to be prolific geothermal reservoirs [63]. There is a strong government focus on facilitating and co-ordinating the re-use and re-purposing of existing gas- and oilfields, including for geothermal use, to support to the energy transition (Nextstep, 2022). The wide-ranging spread of unconsolidated, shallow geology and shallow aquifer systems mean that potential for shallow geothermal systems exists across the country including underground thermal energy storage (UTES).			

Table 20 Regulations and licencing procedure for geothermal systems in the Netherlands

	Deep geothermal (>500m)	Shallow (<500m)
Regulation	Resource regulated under the Mining Act, with separate regulation for environmental impacts	Regulation exists for all shallow geothermal systems under the Water Act. New environmental legislation (the Environment and Planning Act) is expected for 2022 and will affect regulation of all GSHP/UTES systems
Permitting//Licencing	Separate licences are issued for exploration and for production of geothermal energy; free of charge; no automatic conversion of the exploration to exploitation licenses	Licences define requirements for maximum infiltration temperature and water quality measurements, as well as monitoring requirements. All open-loop GSHP systems and large closed loop systems (>70kW) have to be monitored [55].
Issuing authority	Minister of Economic Affairs and Climate Policy; enforced by mining authority	Local planning authority coordinate the licencing/permitting process, including

	Deep geothermal (>500m)	Shallow (<500m)
		consultations with other relevant authorities (mainly the water authority).
Comments	Assessment of licence applications includes consultations with experts from the state geological survey (TNO). Other parties (provinces, municipalities, water authorities, etc., act as advisors to the Ministry during the licensing process [46].	Currently, licences applications can be completed online via a one-stop-shop [56].
Regulations: Geothermal energy is recognised as natural resource in the Netherlands. The resource is owned by the state, but exploration and exploitation activities generally require authorisation from the private landowner [46]. Regulations and licencing procedures are in place, both for deep and for shallow geothermal systems as summarised below.		

Table 21 Policy support for geothermal systems in the Netherlands

Policy mechanism	Deep//Direct- use heating	Shallow geothermal
Investment support, loans and grants	-	ISDE (investeringssubsidie voor Duurzame Energie) starting at € 2.800 up to 10 kW
Insurance/guarantee schemes	RNES Aardwarme, subsidized warranties with a premium payment equal to 7% of the maximum subsidy amount.	-
Feed-in Tariffs/Premiums	SDE++ is a feed-in premium paid based on emission savings (€/tonne CO_2) for up to 15 years, overall budget (all technologies): €13 billion	-
Contracts for Difference	Not used	Not used
Research and innovation funding	Knowledge and Innovation Roadmap Geothermal Energy Research funding ThermoGIS – geothermal resource tool//Map Viewer 'Netherlands Seismic Campaign for Geothermal Energy' (SCAN) project [68] Participant in EU project GEOTHERMICA	'gas-free neighbourhoods' project (total budget: 120 million euros) for high temperature aquifer thermal energy storage (HT-ATES) [68]
Legislative support	Obligation for operators to deposit all geological data with the responsible ministry//Dutch Geological Survey (TNO) Since July 2018, newly built houses can no longer be connected to the gas grid [68].	-
Taxation	-	[3]Recent tax and levy reform lowered electricity taxes and levies to encourage heat pump use

Policy: A number of policy mechanism exists in the Netherlands for geothermal technologies. The main policy mechanism for deep geothermal is the Stimulation of sustainable energy production and climate transition (SDE++) scheme. It is a feed- in subsidy which compensates renewable schemes for the "unprofitable component" of their operation, i.e., the difference between the cost price of the renewable energy or the reduction in CO_2 emissions and the revenue (if any). An overall budget of €13 billion is made available for the SDE++ 2022 [65].

The Dutch government also provides a guarantee scheme (RNES Aardwarmte), under which investors are protected against the financial risks of unsuccessful drilling and lower than expected heat outputs. The available budget in 2021 was €66.66 million [42].

The main policy support for shallow geothermal scheme is the ISDE (investeringssubsidie voor Duurzame Energie), an upfront investment grant.

Assessment of policy impacts

In the last 10 years, the Netherlands has seen an increase in deep geothermal systems from 5 to 28 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.

There is a clear commitment from the government to developing geothermal energy in the Netherlands, and a number of external drivers precipitated the decision to move away from gas (loss of public acceptance for gas developments) [68]. The country's geothermal commitment was first defined in form of a vision for geothermal which was later translated into the Masterplan for Geothermal energy with clear targets and policy support measures.

A timeline of geothermal policy developments in the Netherlands is shown in Figure 15. As for Germany (Bavaria), it highlights the long-term availability of data (e.g., ThermoGIS and SCAN) and government support (e.g., various subsidy and risk guarantee schemes). In addition, the Netherlands has adopted the pragmatic approach of developing regulations as the industry develops (Mijnlieff, 2022, pers comm), resulting in regular revision and amendments to regulation and legislation.

Various policy mechanisms have been put in place to support the countries geothermal ambition, including the Stimulation Sustainable Energy production scheme (SDE+) scheme (which has now been replaced by SDE++) and the government guarantee scheme on drilling risks. Availability of these policies is considered as a key component in the success of deep geothermal development in the Netherlands [64].

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 [68]. 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 [48].

Switzerland

Policy review

Switzerland has moderate potential for geothermal electricity generation but high potential for direct-use heating. The geothermal potential and resource are considerably different from that of Northern Ireland, but Switzerland is included here to provide some policy insights. Table 22 and Table 23 summarise the geological context and policies pertinent to the development of geothermal energy in Switzerland. Geothermal regulations in Switzerland have not been investigated in this report.

Table 22 Summary of geological context and deployment of geothermal energy in Switzerland

	Electricity generation	Direct- use heating	Shallow geothermal
Geothermal potential	Moderate [50]	High [50]	High (25% of heat demand) [58]
System types	Enhanced Geothermal Systems Some Hydrothermal system		Ground Source heat pumps (open-loop, closed loop), aquifer thermal energy storage (ATES)
Geological target	Crystalline basement and fault zones Fractured and/or karstic carbonates		Shallow and near surface geothermal installations possible in most parts of the country [60]
Target depth	-		-
Geothermal gradient	25 to 45°C/km [74]		
Current installed system/capacity	No operational power plants, but there is a noticeable increase in developments of power production projects in the last 12 months [60] [53] 1 EGS project in development (in 2021) [53]	23.8 MW[5]/28 schemes 4 hydrothermal heat projects are in development (in 2021) [53]	Total installed capacity of geothermal heating facilities 2390MW (mostly GSHP from different sources including deep aquifers, tunnels, thermal springs) [53] 1 ATES systems in development (in 2021) [53]
Use	Combined power and heat	Thermal bathing, one district heating network and one application to fish farming [60]	Domestic, commercial and district heating
Geological context: Targets for deep hydrothermal projects for heat and power production are limited to aquifers in sedimentary basins potential, mainly limestone of Triassic or Jurassic age, the top crystalline basement, and fault zones. The potential for hydrothermal systems is considered to be limited in Switzerland, but data hardly exist. In contrast, the potential of EGS is assumed to be large throughout the entire country, but currently the crystalline basement north of the Alps is considered a prime EGS target [60]. Shallow and near surface geothermal installations possible in most parts of the country via a wide range of applications.			

Regulation

The Swiss federal system is organized in three hierarchical levels: municipalities, cantons, and the federal state. It offers a high degree of autonomy to its member states, the cantons [59]. Geothermal systems are regulated at the Canton level by the responsible Water Protection Agencies. There is no specific national geothermal legislation, but the Federal Environmental Protection Law and Water Protection Law applies to all geothermal systems [55]. Regulation is not discussed in this report in further detail as licencing and permitting procedures are likely to vary across the 26 cantons. In the absence of a national legal framework for exploitation and exploration of deep geothermal, several cantons have recently started to modify their mining laws and to include geothermal resources in them to enable regulation and licencing [99].

Table 23 Policy support for geothermal systems in Switzerland

<table>
<tr><th>Policy mechanism</th><th>Deep direct- use heating</th><th>Deep power generation</th></tr>
<tr><td>Investment support, loans, and grants</td><td>Two subsidies for surface and subsurface exploration and development activities of geothermal direct use for heat production, covering 60% of the investment costs associated with the geological risk of finding, assessing and developing a geothermal resource for heat production.
A budget of 30 million CHF//USD per year is allocated for this. An expiry date has not been specified. [53]</td><td>Similar subsidies to those for heat – covering up to 60% of cost of surface exploration and exploration drilling for geothermal power projects up to where the geothermal reservoir has been proven. [53]</td></tr>
<tr><td>Insurance/guarantee schemes</td><td>Pure grants subsidy (as detailed above) acts as risk guarantee</td><td>Geothermal risk guarantee (pre-2018) has been extended to cover up to 60% of the investment. Risk guarantee and subsidy for power projects are in place until 2031 – annual commitment 50 million CHP.</td></tr>
<tr><td>Feed-in Tariffs/Premiums</td><td>-</td><td>Feed in tariff available until 2023, duration of payment is 15 years. [53]</td></tr>
<tr><td>Contracts for Difference</td><td>Not used</td><td>Not used</td></tr>
<tr><td>Research and innovation funding</td><td colspan="2">Financial support for geothermal research and innovation of USD 20 Mill/year, including USD 3 Mill for pilot and demonstration projects [61].
Grimsel test site (underground laboratory in crystalline basement); Bedretto Underground Laboratory for Geoenergies (located 1.5km below surface in 5.2km-long tunnel)
Participant in EU project GEOTHERMICA [61].</td></tr>
<tr><td>Legislative support</td><td colspan="2">Requirement for all types of data and analysis generated by projects that receive government subsidies to be deposited with the Swiss Geological Survey (Swisstopo). Swisstopo is permitted full use of the data, but only selected data sets are being made available publicly.</td></tr>
<tr><td>Taxation</td><td colspan="2">Carbon tax (USD 96/tonne CO_2) on fossil fuels use in stationary heat supply [61].</td></tr>
<tr><td>Comments</td><td colspan="2">Payment for the incentives is collected from end-users through taxation (electricity) and carbon taxes (heat) – any funds that are not spent in the year are being repaid to end-users [61] [Minning (2022, pers comm)]</td></tr>
<tr><td colspan="3">Policy: The Swiss government offers a range of policy support measures for DGE projects. Until recently, the policy focus has been on supporting geothermal power generation. After an extensive revision of the legislative framework in 2017, geothermal policy support is now available for both, direct use heat and power production [53].
Switzerland does not have a national incentive programme for SGE, because this falls under cantonal sovereignty. Most cantons have stopped financial support of SGE because life cycle costs are now economically viable [61]. For this reason, SGE is not included in this table.</td></tr>
</table>

Assessment of policy impacts

A timeline for geothermal policy development in Switzerland is shown in Figure 16.

Switzerland was one of the first countries to introduce a geological risk coverage in the form of a pure grant (Swiss 1987) to support development of geothermal energy on deep aquifers. The 10-year policy, which started in 1987, created a small boom in the exploration and exploitation of hydrothermal resources, resulting in the drilling of 14 deep boreholes (400 to 2600 m) from 1987 to the end of the risk coverage in 1998. Following the end of the geological risk coverage and in absence of other incentives for geothermal, no deep geothermal drilling occurred in Switzerland for nearly ten years except for the Deep Heat Mining (DHM) project of Basel [99]. A second Swiss fund in traduced in 2008 (Swiss 2008) offered coverage to 50% of eligible costs for geothermal power projects, resulting in only one project applying for support. In 2018, the policy was updated (Swiss 2018) and extended to include direct-use heat, covering all activities from preliminary studies to drillings [44].

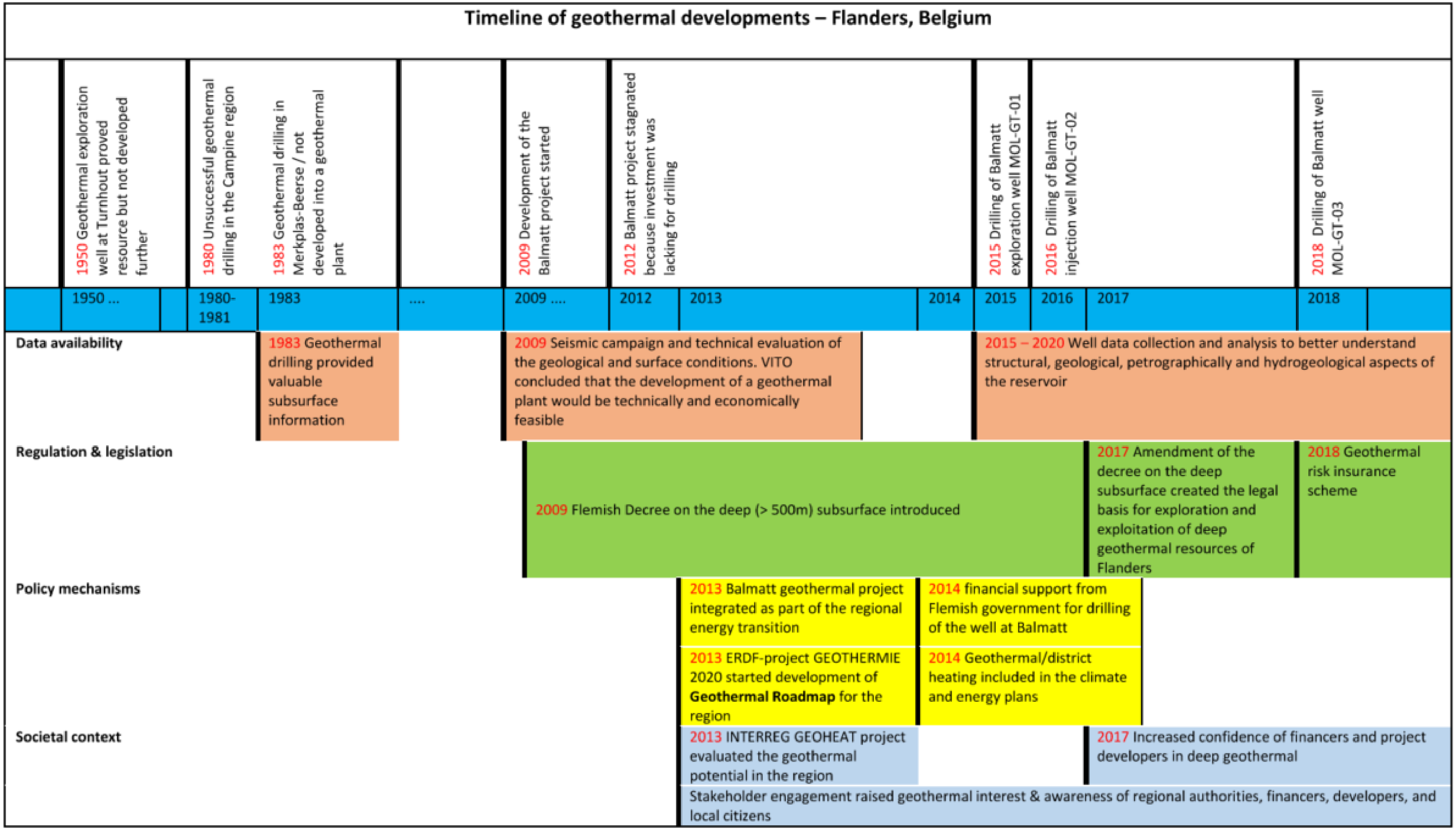
New geothermal incentives were introduced in 2008. At that time, the Swiss federal government solely supported geothermal power generation to encourage decarbonisation of electricity production. Despite the strong policy incentives from the federal government, there is still no operational geothermal power project in Switzerland today. Setbacks in early electricity projects (e.g., induced seismic events at Basel and St Gallen) have meant that some cantons and cities took different pathways, focussing their efforts on geothermal heat production rather than implementing federal objectives for geothermal power generation. The success of these initiatives has led federal authorities to modify their policy [51]. In 2017, revisions of the Energy-Act and the CO2-Act were adopted resulting in a series of revised and new ordinances and policies. The revised legislative framework includes geothermal policy support for both, direct use heat and power production. In 2021, there were four hydrothermal heat projects in development [53]. The payment for policy support is raised through different fiscal routes, i.e., via the taxation of electricity (for geothermal power) and via carbon taxes (for geothermal heat). Unspent funds are repaid to the tax paper via a rebate.

Other grants exist for commercial renewable projects in Switzerland, but have not been captured in the timeline, including grants that are targeted at planning stage tasks such as feasibility studies.

In addition to policy incentives, the Swiss government has also supported the development of a range of research groups and educational programme, including an international Master’s programme and research centre for geothermal energy.

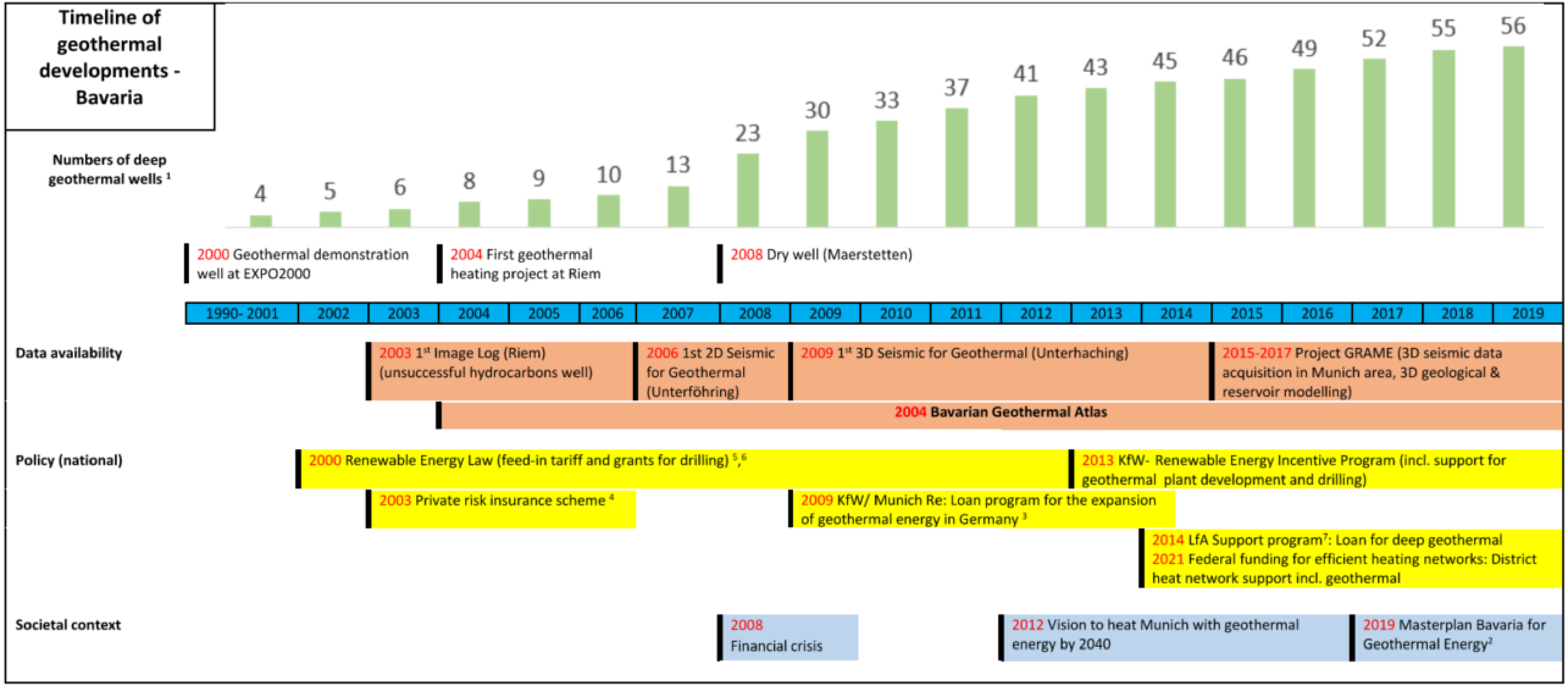
Country Timelines

Figure 13 Flanders (Belgium) timeline of geothermal development



Sources: Bos & Laenen, 2017; Hoes et al. 2021, VITO, 2022

Figure 14 Bavaria (Germany) timeline of geothermal development



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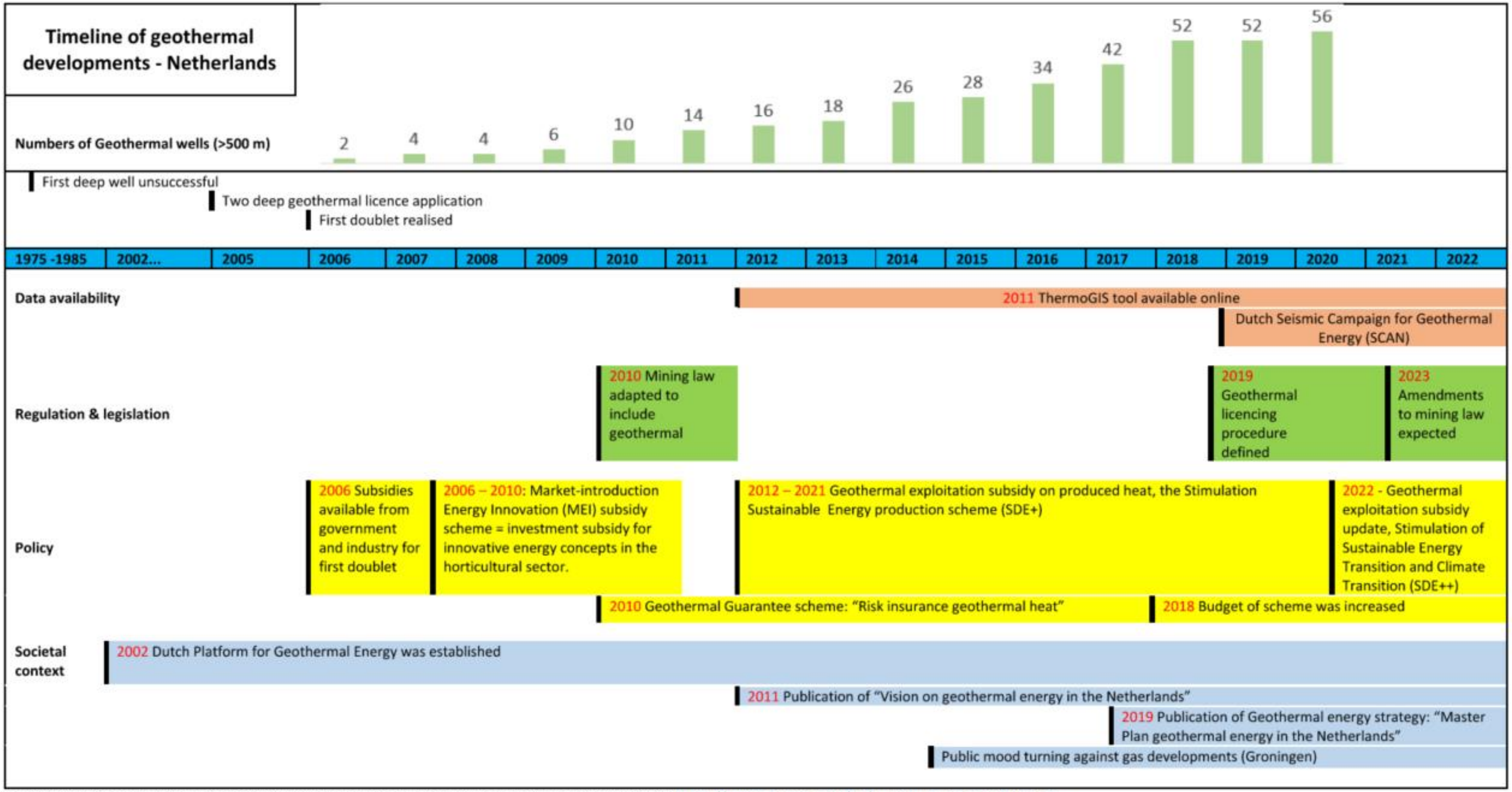
[6] https://de.wikipedia.org/wiki/Erneuerbare-Energien-Gesetz#:~:text=Das%20deutsche%20Erneuerbare-Energien-Gesetz%20%28EEG%202021%29%20regelt%20die%20bevorzugte,Seit%202000%20erweiterte%20es%20schrittweise%20das%20vorangehende%20Stromeinspeisungsgesetz.

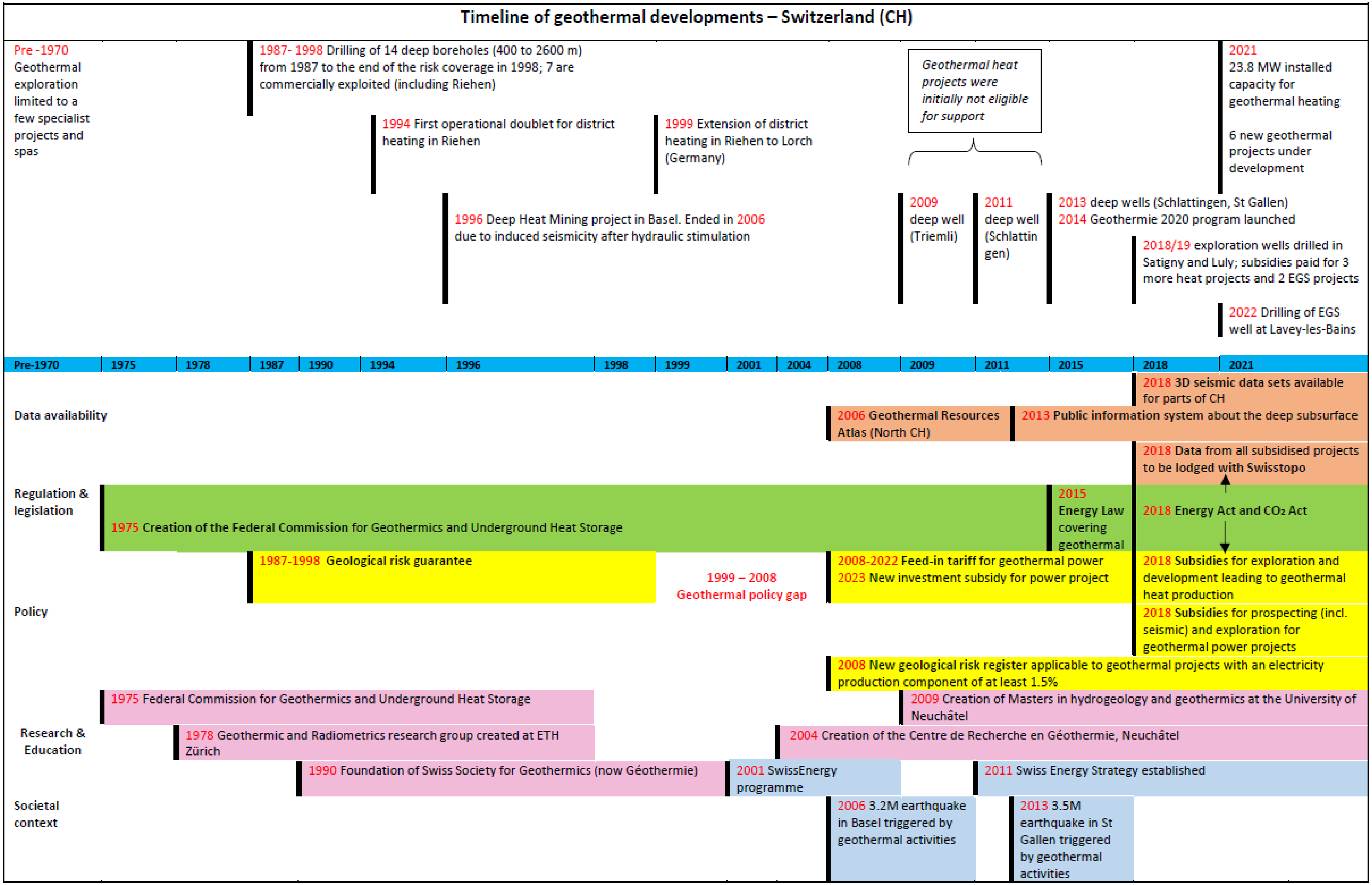
[7] https://www.tiefegeothermie.de/news/lfa-foerderprogramm-fuer-tiefe-geothermie-neu-aufgelegt

Figure 15 Netherlands timeline of geothermal development



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

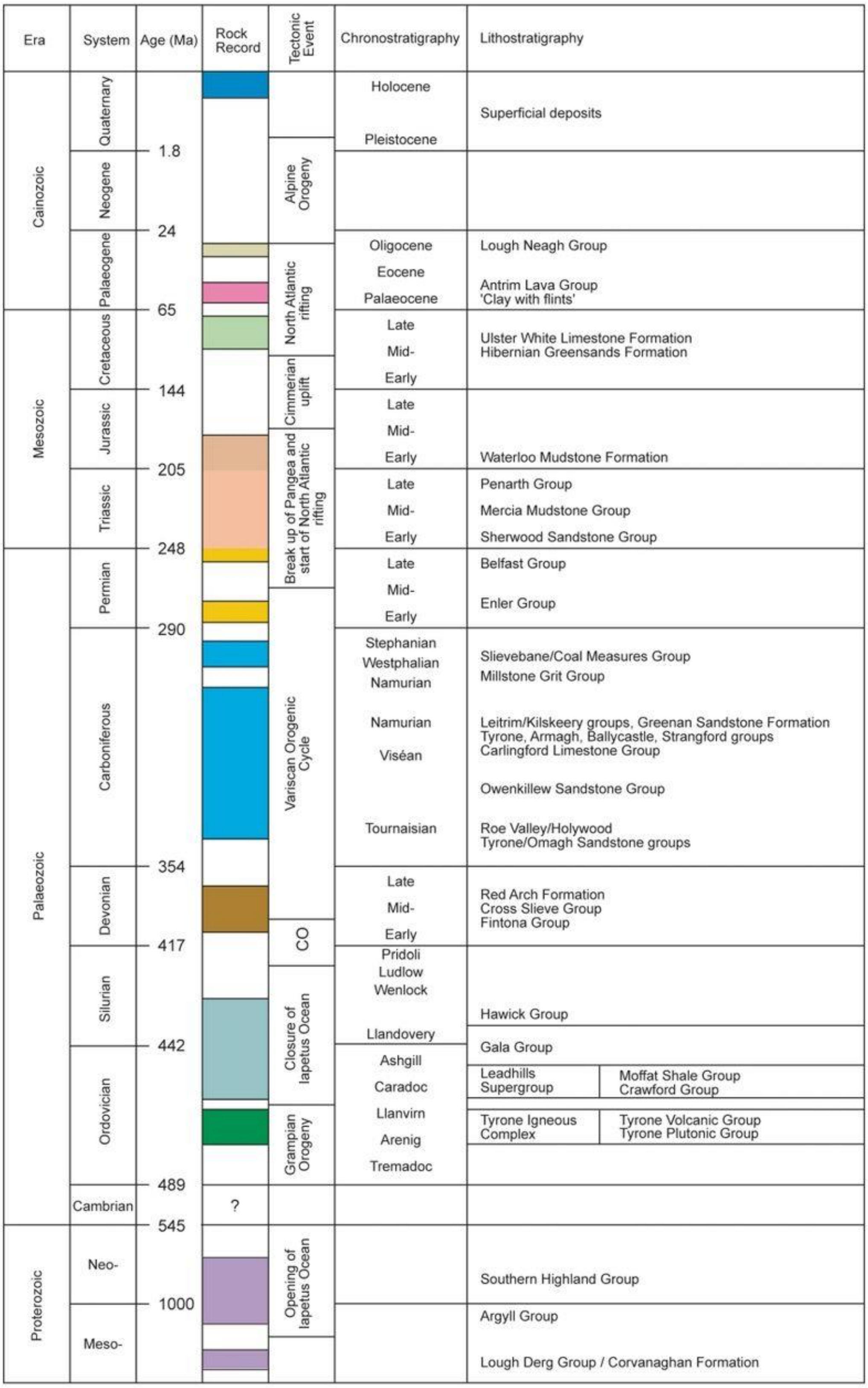
Figure 16 Switzerland timeline of geothermal development



Sources: Altwegg (2015), Breembroe et al., (2013); Ejderyan et al. (2020); Gischig et al, (2021)

NI Geology

Figure 17 Geological succession of the rocks in Northern Ireland [103]



CO - Caledonian Orogeny