Spatial analysis of minewater thermal resources using Scotland as a case study.

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Declaration

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed:

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Abstract

Abandoned flooded mines could act as underground thermal storage or provide ambient heat for district heating networks, collectively known as minewater thermal resources. Despite widespread coalfield areas, minewater thermal resources have not been widely used in the UK. A clearer understanding of how minewater could play a role in heat decarbonisation requires spatial assessment of minewater thermal resources and heat demand.

This thesis investigated four aspects of minewater thermal resources in Scotland. A study of industry experts' perceptions found that thermal storage is a key advantage that distinguishes minewater thermal resources from other low-carbon heating solutions. An assay of mine shafts for different energy storage uses showed there is significant potential across Scotland, with a theoretical total mine shaft volume of 2.9 x10^6 m^3. Three methods of estimating the volume of underground workings were tested, showing a large potential for thermal storage in Scottish mine workings (estimated void space of 10^9 m^3). However, for both shafts and underground workings, data quality and availability mean uncertainties need to be assessed on a site-by-site basis. Finally, calculations of the demand for heating replacement in houses built since 1997, demonstrated that the opportunity to roll out heat networks will evolve over space and time.

These four linked studies were used to classify local authorities by their potential for minewater thermal storage. Regional clusters were defined where large mine volumes were co-located with high heating replacement demand. The Greater Glasgow and Lanarkshire region, encompassing five local authorities, had the highest potential for using minewater thermal resources with an estimated volume of 4.37 x10^8 m^3 and the highest demand for heat, with over 159,000 heating replacements in houses built since 1997. Regional clusters demonstrate the need for more collaboration between local authorities and could aid in the future strategic planning for minewater resources across Scotland.

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1. CHAPTER ONE: Introduction

1.1 Background and case study area

Providing space heating to buildings contributes around 8% of global greenhouse gas emissions (IEA, 2023a). In northern countries, such as the UK, that figure is much higher. In the UK, domestic heating contributed 18% of total greenhouse gas emissions (NAO, 2024). Therefore, heat decarbonisation is vital for climate change mitigation and meeting net zero target. Despite this large emission contribution, heat decarbonisation progress has been slow compared with other sectors. There are many methods by which we can transition away from fossil fuel heating to electrified solutions including heat pumps and district heat networks. To achieve heat decarbonisation, wide scale systematic change will be needed, something that is well summarised by MacKay (2009), "*If everyone does a little, we'll achieve only a little*" (MacKay, 2009, pg.3).

The water in abandoned flooded mines, known as minewater thermal resources (MWTR), can be used as a heat source or as thermal storage. Warm water from flooded mine voids can be brought to the surface and passed through a heat exchanger to transfer its heat into a heat pump, where it can be boosted and used to heat buildings (Walls *et al.*, 2021, Monaghan *et al.*, 2022a). Mine voids could also act as inter-seasonal storage for district heating networks or curtailed wind (Hahn *et al.*, 2019, Dassow *et al.*, 2024; Shipton *et al.,* 2024). The UK has an abundance of abandoned coal mines, and The Mining Remediation Authority estimates that 25% of UK towns and cities are within the coalfield area MRA. (2024b). However detailed mapping on heat resource has not been carried out Farr and Busby (2021) stated that national scale mapping was crucial for *"local authorities, developers, and planners"* to assess the potential for heat extraction or storage in coalfield areas across the UK.

Thermal storage potential often relies on having a large enough void to provide sufficient inter-seasonal efficiency (Mangold and Deschaintre, 2015), however estimating the voids of coal mines that closed decades ago is not straightforward. By having a good estimate of the volume of a void, the need for expensive geophysical or ground investigation techniques being used prematurely could be avoided. It also negates the need to access the sites in person before it is necessary, avoiding potential issues with land access and public engagement or perceptions of the works. Having an idea of the size of a void could also help to select and scale any future geophysical or geotechnical investigation works and provide realistic estimates for the storage potential. Without a good estimate of how much heat or thermal storage the mine resources could provide, convincing investors and developers to pursue minewater heating solutions will be difficult.

1.1.1 Spatial analysis of minewater resources

At the start of this PhD project in April 2022, there were no published spatial analyses of minewater resources in Scotland or the UK, apart from temperature maps of British coalfields (Farr *et al.*, 2021). In 2023, the Mine Water Geothermal Resource Atlas for Scotland (MiRAS) was published (SpatialHub.Scot, 2023). This method, as described in Walls *et al.* (2024) uses minewater depth, seam depth, and the number of overlapping seams, to assess potential for minewater heat extraction across Scotland. A suitable area of 370 km^2 was identified spanning nineteen Scottish local authorities, with North Lanarkshire having the greatest potential (90.9 km^2, Walls *et al.*, 2024). This map does not quantify the heat resource for underground workings, but it does incorporate heat from 'at surface' minewater resources, such as minewater treatment facilities, as quantified in Walls *et al.* (2022).

Following this in 2024 and 2025, opportunity maps were developed by the Mining Remediation Authority (MRA) for Wales and ten cities[1] across England (Welsh Government, 2024, MRA, 2024a, Data.gov.uk, 2025). These opportunity maps use underground working depths, minewater levels, minewater recovery status, and evidence of open cast mining, to assign areas to one of three opportunity levels ("Good", "Possible" or "Challenging") for open loop minewater heat extraction systems (MRA, 2024a). These opportunity maps do not quantify either the area of land underlain by mine workings as Walls *et al.* (2024) does, or the amount of heat that could be extracted from the identified areas. The English opportunity maps were incorporated by DESNZ into Heat Network Zoning Reports (Monaghan *et al.*, 2025), which indicate the opportunities for heat networks for cities across England (DESNZ, 2025a).

Outside the UK, Gzyl, and Skalny (2025) present a method for assessing minewater heat extraction potential based on the proximity of heat users to 50 active or decommissioned mines in the Upper Silesian Coal Basin in Poland. The proximity (<1 km) of mines to six weighted categories of 'heat receptors' (e.g. 'multiple family housing', 'large scale public buildings' or 'large-scale production plants') was assessed. The weightings of the categories were based on their potential for using minewater heat. The sum of these weights for each mine were ranked and sorted into three categories of high, medium, or low potential (Gzyl, and Skalny, 2025). They concluded there was a high potential for using minewater thermal resources in the Upper Silesian Coal Basin as it is highly urbanised. However, this method did not consider characteristics of the mines such as size, depth, or minewater temperature.

[1] The ten English cities are: Birmingham, Bristol, Coventry, Leeds, Greater Manchester, Newcastle, Nottingham, Sheffield, Stoke-on-Trent, and Sunderland (MRA, 2024a).

There are several limitations with these four sets of opportunity maps. Firstly, the English city maps only assess mine workings within the city boundaries (MRA, 2024a). Underground mine workings will extend beyond city limits but could still be used to meet heat demand within the city. Secondly, the mapped opportunity areas are not easily 'translated' for a non-specialist audience, into an amount of heat, storage capacity, or buildings that could be heated. Thirdly, none of these four approaches consider availability or proximity of other heat sources. None of the UK maps consider heat demand spatially as part of the analyses. Gzyl, and Skalny (2025) consider proximity of heat demand to mines, but do not quantify whether those mines could meet the demand.

There seems to be a disconnect between supply and demand, even though the co-location between mining areas and settlements is often stated as a major advantage for using minewater resources (Farr *et al*., 2021, Farr and Busby, 2021, Monaghan *et al*., 2022a, MRA, 2024b, Walls *et al.*, 2024). Therefore, there is a need to spatially assess the co-location of minewater thermal resources and heat demand in more detail and situate it in the wider context of heat decarbonisation policy.

1.1.2 Case study area

Scotland has been chosen as the location for this research due to the good availability of spatial data, its large number and range of coal mines and long mining history. Additionally, there is a large range of spatial variability of domestic heating in Scotland, from city centre flats to remote rural homes. Many rural properties in Scotland are off the gas grid and use oil, LPG, or solid fuel for heating, so different decarbonisation approaches will be needed in different areas. The Scottish Government has taken a spatial approach to heat decarbonisation through the Local Heat and Energy Efficiency Strategies (LHEES).

1.2 Research aims

This thesis will examine the spatial variability of coal mines across Scotland and their potential for being used for thermal energy extraction or energy storage and the spatial and temporal evolution of heat demand. Without knowing the size of the potential energy resource, investment in minewater resources will be more difficult and the role that minewater could play in the wider decarbonisation of heat will not be clearly understood.

This spatial and temporal approach is developed using Scotland as a case study but could be applied elsewhere to assess and quantify minewater thermal resources and provide evidence of when and where they could best be strategically deployed to advance the decarbonisation of heat.

1.3 Structure of the Thesis

This thesis uses an interdisciplinary, mixed methods approach to investigate minewater thermal resources in the specific context of Scotland.

Chapter 3 and 4 have been written and published as standalone journal articles, each containing their own abstract, introduction, literature review, methods, results and discussions. As a result, there may be some overlap between the different literature reviews. Chapters 5 and 6 have been written as thesis chapters, each with their own discussion sections. Chapter 7 is a synthesis of findings from the two papers and two chapters.

Chapter 2 – Literature review in covering heat decarbonisation, minewater thermal resources, Scottish coal mining, and the Scottish housing stock and heating types.

Chapter 3 was published in Earth Science Systems and Society, Geological Society of London on 29th November 2024.

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Chapter 5 – A comparison of different methods of estimating mine void volume and an assessment of risk.

Chapter 6 – A method of investigating future heating replacement demand.

Chapter 7 – Synthesis of Chapters 3,4,5, and 6.

Chapter 8 – Conclusions and recommendations

1.4 Acknowledgement of the miners

It is important to recognise the miners who excavated these mines often with only hand tools and through back-breaking labour, until the widespread use of mechanical coal cutting in the early 20th Century (Duncan, 2005). This human aspect of minewater thermal resources is often overlooked and we are removed from the coal mine in both time and distance; the underground is difficult to conceptualise (Roberts *et al.,* 2021), and mining industry faced decades of decline before eventually the last deep mine, Kellingley Colliery, closed in 2015. The author George Orwell described the conditions and experiences of coal miners in 1930s England in his book 'The Road to Wigan Pier' (Orwell, 1937). His descriptions of the environment of the coal mine are graphic and visceral, describing the assault on all the senses and likening it to hell, or at least how he imagines hell "*Most of the things one imagines are in hell are there – heat, noise, confusion, darkness, foul air, and above all, unbearably cramped space. Everything except fire"* (Orwell, 1937, p.18). He describes the heat as being variable between mines, but that it was *"suffocating"* in some mines, and he describes a "*dusty fiery smell which seems to be the same in all mines."* (Orwell, 1937, p.18). The knowledge of these places is soon going to be lost from living memory, as miners who started in the 1980s as young men, approach their 60s and 70s (Webber, 2025). The time that Orwell describes in the Road to Wigan Pier is long gone from the collective consciousness. *"In the metabolism of the Western world the coal-miner is second in importance only to the man who ploughs the soil." (Orwell, 1937).*

Having an awareness of the history of a coal mining region could be useful for minewater thermal for two reasons. Firstly, having an understanding of the social history will help to understand the communities that are living in former coal mining areas today. Secondly knowledge of the age and type of coal mining could help determine the void space, and potential thermal energy resource (explored in Chapter 5), as well as the potential for collapse, whether the mine was filled in or issues that may arise from gassy coals. There is also an opportunity to learn from the past and not repeat the mistakes of the closure of the coal mine industry. The transition away from fossil fuels needs to be a fair and just transition which carefully considers the needs of the people involved.

2. CHAPTER TWO: Literature Review

This literature review examines the context for heat decarbonisation and minewater thermal resources in Scotland. Firstly, heat decarbonisation and the specific policies in Scotland will be examined. Secondly, minewater thermal resources will be described and a review of the parameters of thermal storage will be carried out. Thirdly, the contextual information specific to Scotland as a case study will be discussed: the history of Scottish coal mining in and the Scottish housing stock and heating types.

2.1 Heat decarbonisation

Heat decarbonisation refers to changing the way that space heating and hot water are provided, away from fossil fuels such as gas, oil and coal, and towards electric forms of heating. This will be critical for reaching net zero. Globally, space heating contributes 8% of global greenhouse gas emissions (IEA, 2023a). In the UK, providing heat for the 28 million homes contributed approximately 18% of the UK's total greenhouse gas emissions in 2021[2] (UK Government, 2021, House of Commons, 2024, NAO, 2024). Across the UK, there are approximately 25.5 million homes using fossil fuel boilers (Shepheard *et al.*, 2024a).

There are multiple ways by which heat can be decarbonised, such as heat pumps, electric radiators, or storage heaters, provided that the supply of electricity is also decarbonised (Lowes *et al.*, 2020a, Guar *et al.*, 2021, Wang and He, 2021, Sissons, 2023). Non-electric alternatives include bioenergy and solar thermal (Lowes *et al.*, 2020a). Demand reduction will also be important in the decarbonisation of heat, so there is also a need for increasing energy efficiency of buildings (Lowes *et al.*, 2020a).

Communal or district heating systems (Figure 2.1) is one solution for the transition away from fossil fuels (Buffa *et al.*, 2019). Traditional high temperature district heating networks distribute heat generated from combined heat and power plants (CHP) (Lund *et al.*, 2010, Sartor and Dewallef, 2018, Millar *et al.*, 2019) or gas engines (Vogel *et al.* 2016). These are known as third-generation district heating networks (Millar *et al.*, 2019). A fifth-generation district heating and cooling (5GDHC) network is defined as simultaneously providing heating and cooling through a network that has a temperature less than 45°C as shown in Figure 2.1 (Meibodi and Loveridge, 2022). Heat sources for 5th generation heat networks include, multiple renewable or low carbon sources such as energy from waste or waste industrial heat (Di Lucia and Ericsson, 2014), and ambient heat sources like rivers and lakes (Lund and Persson, 2016, Gaudard *et al.*, 2019, Jung *et al.*, 2021), wastewater (Hepbasli *et al.*, 2014, Zhang *et al.*, 2023), and

[2] The UK's total greenhouse gas emissions in 2019 was 454.8 $MtCO_2e$ (BEIS, 2021). 77.3 MtCO2e from approximately 28 million domestic dwellings.

abandoned mines, which is the focus of this research. Ambient heat sources call for a more decentralised, localised approach to heat supply, rather than the centralised approach of the current national gas network. Heat decarbonisation is inherently spatially localised, as thermal energy cannot be transported very far (Ma *et al.,* 2009, Jung *et al.,* 2022), it cannot be piped long distances (100s -1000s km) to people's homes like gas, or travel through wires on pylons like electricity, it needs to be used close to where it is generated.

Energy storage will be crucial in a future decarbonised heat system (Marsden *et al.,* 2024) due to reliance on intermittent renewable electricity generation, from wind and solar, and the decentralised nature of district systems. Thermal energy storage will be discussed further in Section 2.3 of this literature review. If net zero targets are to be reached, there will need to be a large-scale transition in the way that homes are heated in the next 20 years. However, heat decarbonisation also provides opportunities for other benefits to society from ensuring that homes are heated efficiently and cost effectively. Heat pumps can be cheaper to run than fossil fuel boilers due to their high efficiency (Burns *et al.,* 2021) which could lead to a reduction in energy bills for many households and lift people out of fuel poverty (Shepheard *et al.* (2024a). Living in a cold home has also been shown to lead to negative health outcomes (Kizilcec *et al.*, 2023) especially for vulnerable or elderly households, so lowering bills and increasing efficiency would help ensure that people could live in a warm home.

Despite the potential for multiple benefits, progress has been slow to decarbonise heat compared with other sectors such as electricity generation (House of Commons, 2024). Governments have a responsibility to act decisively to ensure that this transition can take place in a fair and efficient manner. The next section will examine heat decarbonisation in the Scottish context.

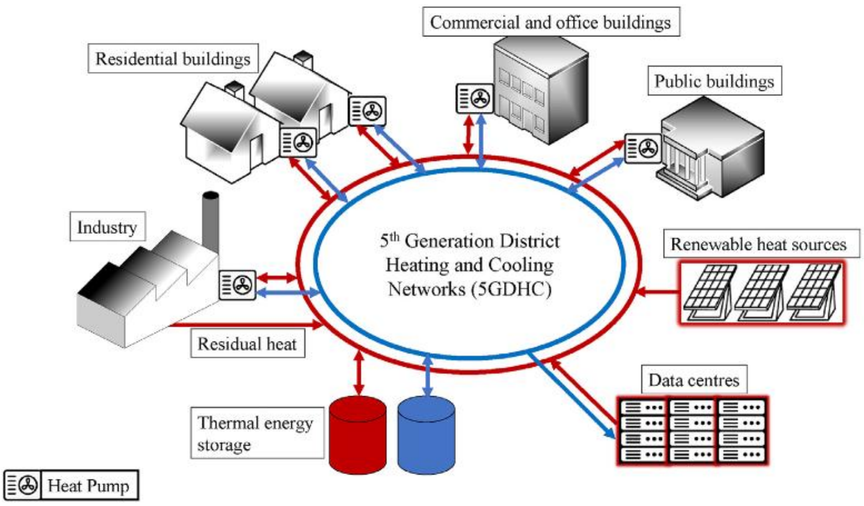

Figure 2.1. A diagram of a typical 5th Generation District Heating and Cooling network, from (Meibodi and Loveridge 2022).

2.1.1 Heat decarbonisation in Scotland

In Scotland, there are approximately 2.5 million occupied domestic dwellings, accounting for approximately 30% (44 TWh) of the total Scottish energy consumption and 13% of Scotland's total greenhouse gas emissions[3] (Scottish Government, 2021). In 2019, the Scottish Government committed to reaching net zero emissions by 2045, five years earlier than the rest of the UK, and to reach a 75% reduction in emissions by 2030 (compared with 1990 levels; Climate Change (Emissions Reduction Targets) (Scotland) Act, 2019). In 2021, only 11% of homes in Scotland (278,000) were using a renewable or low emissions heating system and over 80% (2.25 million) were using mains gas (Scottish Government, 2021). This demonstrates the scale of the challenge facing the Scottish Government, and they have recognised that without decarbonising domestic heating it will be impossible to reach net zero (Scottish Government, 2023). Therefore, action is needed to support and increase demand for low carbon heat across Scotland.

The next section will examine the approach that the Scottish Government is taking by providing an overview of three aspects of Scotland's heat decarbonisation policies, i.e., the Heat in Buildings Strategy, the Local Heat and Energy Efficiency Strategies (LHEES) and the Heat Networks Act.

2.1.1.1 Heat in Buildings Strategy

In 2021, the Scottish Government published the Heat in Buildings Strategy, setting out their ambitions for decarbonising heating by reducing the use of 'polluting heating systems' in Scotland. The term 'polluting heating systems', is defined as heating systems that produce greenhouse gas emissions at the point of use (also referred to as 'direct emissions heating systems'; Scottish Government, 2023, Building (Scotland) Amendment Regulations 2023). This includes all boilers burning fossil fuel, but also those that use biomass or other biofuels because they produce CO_2 emissions (Scottish Government, 2023). In contrast "clean heating systems" do not produce greenhouse gas emissions at the point of use (Scottish Government, 2023). The Scottish Government have recognised that without moving away from these "polluting heating systems", it will be impossible to achieve their net zero by 2045 target (Scottish Government, 2023). In the Heat in Buildings Strategy (2021) they say they will achieve net zero by converting at least one million homes using mains gas, 170,000 homes using high emissions fuel (e.g. oil, LPG, solid fuels), and 50,000 non-domestic buildings, to a form of 'zero emissions heating system' by 2030. This move away from polluting heating equates to a reduction in fossil fuel consumption of around 28 TWh (21 TWh of which is natural

[3] Non-domestic buildings account for 12% of the total energy consumption (17 TWh) and 7% of the total greenhouse gas emissions (Scottish Government, 2021).

gas; Scottish Government, 2021). As part of the Heat in Buildings Strategy, the Scottish Government introduced the New Build Heat Standard (NBHS; Scottish Government, 2024a), through a change to building regulations, prohibiting the use of 'direct emission heating systems' in buildings built after 1st April 2024 (The Building (Scotland) Amendment Regulations 2023).

The Heat in Buildings Strategy led to the creation of the Heat in Buildings Bill, the main aims of which are to legislate to outlaw 'polluting heating systems' in Scotland after 2045 and introduce a minimum energy efficiency standard that should be reached by homeowners by 2033 and reached by landlords by 2028, respectively (Scottish Government, 2023). Following a public consultation the Bill was revised in April 2025, shifting the responsibility for decarbonisation from householders to Government (Scottish Government, 2025a). On 18th November 2025, it was announced by the Housing Secretary, Màiri McAllan, that the Heat in Buildings Bill would now not be debated in the Scottish Parliament until after the 2026 elections, due to delays with the UK Government's 'Warm Homes Plan' (Findlay, 2025, Scottish Government, 2025b). In the interim, the Scottish Government have published a draft version of the Bill (Scottish Government, 2025b).

2.1.1.2 Local Heat and Energy Efficiency Strategies

In 2022 the Scottish Government created a statutory instrument that required all 32 Scottish local authorities to publish a Local Heat and Energy Efficiency Strategy (LHEES) by the end of 2023 (The Local Heat and Energy Efficiency Strategies (Scotland) Order 2022). This required each local authority to set out a long-term strategy of how they intend to improve energy efficiency and to designate heat network zones across the authority area (Scottish Government, 2022a). If the Heat in Building bill discussed in Section 2.1.1.1, becomes law, households within a heat network zone will be required to connect to a heat network when it is constructed (Scottish Government, 2023).The government ran two pilots of these strategies between September 2017 and December 2019 to test the methodology and assess data sources (Scottish Government, 2019, Scottish Government, 2020a). As of December 2024, 26 local authorities (81%) had published their LHEES, and 3 had published draft LHEES for public consultation.

2.1.1.3 Heat Networks Act

There is a significant opportunity for heat networks especially among densely populated city regions. In November 2023, 33,000 buildings in Scotland were connected to a heat network (Scottish Government, 2023). The Heat Networks (Scotland) Act 2021 sets out targets for heat networks in Scotland. By 2027, 2.5 TWh of heat will be provided by heat networks, increasing to 6 TWh by 2030, which would account for 3% and 8% of current total heat supply (Scottish

Government, 2022b). In 2023 the Scottish Government estimated that heat networks "could grow to supply between 17.1 – 32.1% of Scotland's total heat demand" (Scottish Government, 2023).

All this points to the need to explore all available options for heat decarbonisation that could be used in Scotland. Heat from abandoned mines could be a source of ambient heat for heat networks, which is the topic of the following section.

2.2 Minewater thermal resources

Heat can be extracted from water in abandoned flooded mines and can be used to provide a source of low-carbon heat for domestic or commercial buildings or hot water, using heat exchangers and heat pumps (Banks *et al.*, 2004, Watzlaf and Ackman, 2006, Banks, 2012, Bailey *et al.*, 2013, Ramos *et al.*, 2015, Walls *et al.*, 2021). Additionally, abandoned mines are increasingly being investigated as a thermal storage medium, for the inter-seasonal storage of heat (Bracke and Bussmann, 2015, Hahn *et al.*, 2018), which will be discussed in Section 2.3.1, in the wider context of underground thermal energy storage (Section 2.3).

2.2.1 Minewater heating and cooling

Minewater heating and cooling schemes as of 2025 are summarised in Table 2.1 (UK) and Table 2.2 (Europe and North America) , the tables include key parameters, such as location, depth and minewater temperature. Currently in the UK there are two operational minewater thermal projects, both in Gateshead (Banks *et al.*, 2022). One scheme is owned by Lanchester Wines to provide heat and hot water to their warehouse facilities at two sites: Nest Road and Abbotsford Road (Table 2.1, Banks *et al.*, 2022, Lanchester Wines, 2023, TownRock Energy, 2025a). The other scheme in Gateshead is owned by Gateshead Council and is a district heating network which heats several commercial and industrial buildings and 1250 council owned homes (Table 2.1, IEA, 2023b; MRA, 2023b; Monaghan et al., 2025). There is also a minewater thermal energy research facility in Glasgow, known as UKGEOS, which has been constructed by the British Geological Survey (Table 2.1, Monaghan et al., 2022b; UKGEOS, 2023).

In Europe there are more well-developed examples of this technology, notably the Mijnwater scheme in Heerlen in The Netherlands, discussed in more detail below (Section 2.2.1.1), which has been operational since 2008 (Verhoeven *et al.* 2014), and in Mieres, Asturias in Spain which provides heating and cooling to a university and hospital (Menéndez *et al.*, 2020, Walls *et al.*, 2021).

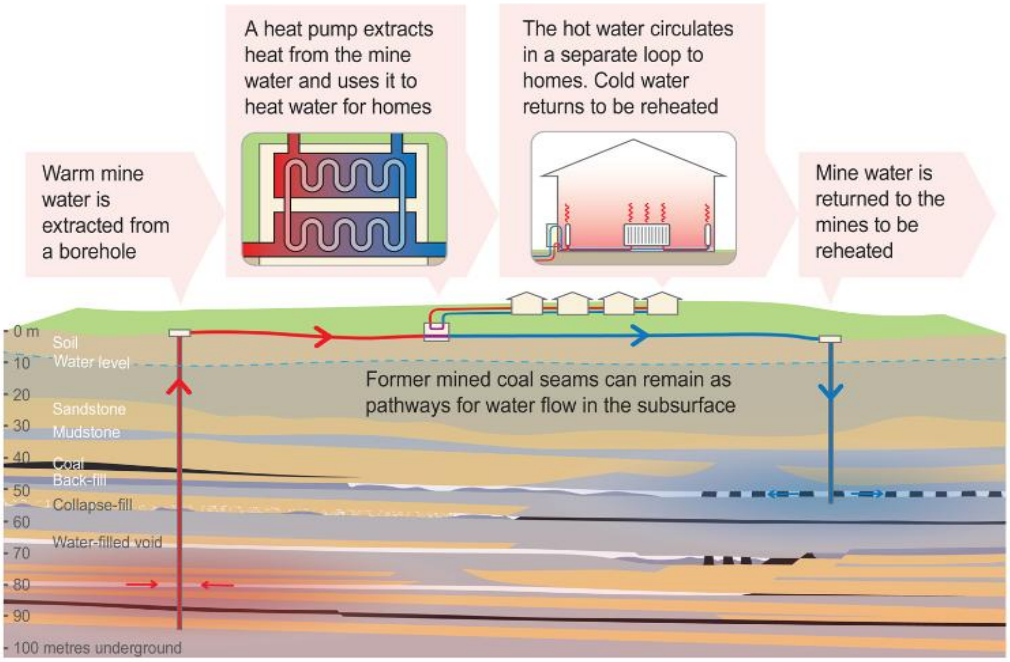

Figure 2.2: A diagram showing how minewater is used for space heating from Monaghan et al. (2022b).

2.2.1.1 Mijnwater, Heerlen, The Netherlands

One of the largest minewater geothermal schemes in operation in the world is the Mijnwater scheme in the city of Heerlen in The Netherlands (Verhoeven *et al.* 2014; Ramos *et al.* 2015). In 2003, the municipality of Heerlen first started investigating the potential of using the abandoned mine workings beneath the city to provide renewable heat for the future (Mijnwater, 2023). Two years later, the pilot phase Mijnwater 1.0, began with drilling five wells into the mine workings of Oranje Nassau colliery, which had six main mine levels and covered an estimated area of 50 km^2 (Ferket *et al.*, 2011). Two wells were drilled to a depth of 700 m to abstract warm water at a temperature of 28°C and two wells to abstract cooler water at a temperature of 16°C from a depth of 250 m. The fifth well returns cooled hot water and heated cool water (temperatures between 18-22°C) back to the mine workings at a depth of 350 m (Verhoeven *et al.*, 2014, Ramos *et al.*, 2015, Walls *et al.*, 2021, Østergaard *et al.*, 2022). In 2008, the minewater thermal plant, known as 'Gen Coel', was opened, initially providing heat to the Heerlerheide Centrum: a complex of homes, offices, supermarkets, and community facilities and the Central Bureau of Statistics (Verhoeven *et al.,* 2014, Mijnwater, 2020). In 2013, a private company known as Mijnwater B.V was established to operate the minewater scheme, with the municipality of Heerlen as its main shareholder, that is operated as a social enterprise for the city (Renewables Networking Platform, 2020). There are approximately 8 km of underground pipes which make up the network (Mijnwater, 2023), which consist of an insulated pipe network for the warm water and two uninsulated pipe networks for the cool water (Østergaard *et al.* 2022). Currently there are 350 homes and 9 office buildings, including the City Hall, connected to the network with several more connections being prepared (Mijnwater, 2023).

Numerical modelling of the fluid flow and heat transfer within the Oranje-Nassau mine showed that there was a potential for thermal breakthrough or feedback within the mine between the abstraction and reinjection boreholes (Ferket *et al.* 2011). This would mean that the hotter areas would cool down and the cooler areas would heat up, causing the temperatures in the mine to average out. Therefore, when the pilot scheme was updated to a full-scale system in 2014, it was reconfigured to make greater use of thermal storage instead of using the mine as a source of heat for the district heating network (Verhoeven *et al.* 2014; Walls *et al.* 2021). The updated system incorporates waste heat to avoid depleting the heat in the minewater reservoirs (Buffa *et al.* 2019). This waste heat comes from decentralised sources such as a data centre, industrial processes, supermarket refrigerators and return flow from space cooling (Verhoeven *et al.* 2014; Boesten *et al.* 2019). Boesten *et al.* (2019) describe this system as being an “urban smart DHC (district heating and cooling) grid” and Buffa *et al.* (2019) describes it as “one of the most advanced 5GDHC networks” currently in operation due to technical solutions implemented at this project.

Table 2.1: Minewater heating and cooling schemes in the UK as of 2025, which use abandoned coal mines

Minewater Scheme	Region	Year opened	Depth (m bgl)	Minewater temp (°C)	End Use	References
Shettleston	Glasgow, Scotland	1999 (no longer operational)	100	12	16 social housing apartments Currently unused due to maintenance issues and lack of contractors.	Banks *et al.*, 2009; Ramos *et al.*, 2015; Walls *et al.*, 2020; Walls *et al.*, 2021
Lumphinnans	Fife, Scotland	2000 (no longer operational)	170	14.5	18 social housing apartments Decommissioned due to reinjection BH being clogged by ochre.	Banks *et al.*, 2009; Ramos *et al.*, 2015; Walls *et al.*, 2021
Cryant	West Glamorgan, Wales	Pilot site (no longer operational)	Abstraction: 63 m bgl. Reinjection: 63.9 m bgl.	11.5	Large farmhouse, farm workshops and an adjoining physiotherapy centre .	Walls *et al.*, 2021
Caerau	Bridgend, Wales	Feasibility study only	230	20.3	Feasibility study only.	Brabham *et al.* 2019
Markham	Bolsover, Derbyshire, England	2012	235	13-14	Trial submersible standing column heat pump to heat office buildings.	Athresh *et al.*, 2015; Burnside *et al.*, 2016a; Banks *et al.*, 2019; Walls *et al.*, 2021
Caphouse	Overton, Wakefield, South Yorkshire, England	2016 (no longer operational)	197	14 - 15	National Coal Mining Museum of England – currently not operational following research phase.	Burnside *et al.*, 2016b; Banks *et al.*, 2019; Walls *et al.*, 2021
Dawdon	County Durham, England	2011 (pilot scheme). 2025 (full scale heat network)	Treatment facility on surface	18-20	Initially an open loop pilot system. Full scale heat network to provide heat for 750 new homes on the Seaham garden village development.	Bailey *et al.*, 2013; Walls *et al.*, 2021; MRA, 2023a; Durham County Council, 2025; Vital Energy, 2025
Lanchester Wines – Abbotsford Road	Gateshead, Tyne and Wear, England	2018	Abstraction: 110 m bgl. Reinjection: 155 m bgl.	11-13	Wine storage warehouse. Provides 2.4 MW_{th} of heat. CAPEX cost = £3.5 million	Walls *et al.*, 2021; Banks *et al.*, 2022; TownRock Energy, 2025a
Lanchester Wines – Nest Road	Gateshead, Tyne and Wear, England	2018	Abstraction: 131 m bgl. Reinjection: 280 m bgl.	13-14	Wine storage warehouse. Provides 1.2 MW_{th} of heat. CAPEX cost = £1.5 million	Walls *et al.*, 2021; Banks *et al.*, 2022; TownRock Energy, 2025b
Gateshead	Gateshead, Tyne and Wear, England	2023	150	15	Offices, municipal buildings, a large arts centre, an industrial lubricants factory, and 1,250 council owned homes (initially 350 homes in 2023). Installed capacity of approx. 6 MW_{th}. Total cost of the scheme = £15.2 million.	IEA, 2023b; MRA, 2023b; Monaghan et al., 2025.

UKGEOS	Glasgow, Scotland	2023	50 – 85 m bgl	12	A BGS and NERC field research facility.	Monaghan *et al.*, 2022b; UKGEOS, 2023.

Table 2.2: Minewater heating and cooling schemes in Europe and North America, sorted by country.

Minewater Scheme	Year opened	Mineral mined	Depth (m)	Minewater temperature (°C)	End Use	References
Canada						
Spring hill	1989	Coal	140	18	Factory building	Watzlaf and Ackman, 2006; Hall *et al.*, 2011; Ramos *et al.*, 2015
Czech Republic						
Jeremenko Mine	2006	Coal	n.d.	26-29	Administrative buildings and employee baths	Walls *et al.*, 2021
Germany						
Alsdorf, NRW	n.d.	Coal	890	26	Office buildings	Ramos *et al.*, 2015; Chu *et al.*, 2021
Robert Müser, NRW	n.d.	Coal	570	20	Two schools and mine drainage station	Kallesøe *et al.*, 2019
Zeche Zollverein, NRW	2000	Coal	1000	33	Museum and design school	Weiber and Pohl, 2008; Schueco. 2022; Chu *et al.*, 2021
Ehrenfriedersdorf, Saxony	1997	Tin	110	10	Mining museum	Weiber and Pohl, 2008; Ramos *et al.*, 2015; Chu *et al.*, 2021
Freiberg, Saxony	2009	Silver	60	10.2	Castle, museum, and university building	Hall *et al.*, 2011; Ramos *et al.*, 2015; Chu *et al.*, 2021
Marienberg, Saxony	2007	Uranium	144	12	Swimming pool, commercial buildings	Weiber and Pohl, 2008; Hall *et al.*, 2011; Ramos *et al.*, 2015; Chu *et al.*, 2021
Wettelrode, Saxony-Anhalt	2013	Coal	283	13	Mining museum	Ramos *et al.*, 2015; Chu *et al.*, 2021

The Netherlands						
Heerlen	2008	Coal	250 and 700	16-19 30-35	300 dwellings, a college, hotel, sports centre, office buildings, data centre	Hall *et al.,* 2011; Ramos *et al.,* 2015; Walls *et al.,* 2021
Norway						
Folldal	1988	Copper, Zinc and Sulfur	600	6	Show cave at a mining museum. (Replaced by air source heat pump in 2011)	Hall *et al.,* 2011; Ramos *et al.,* 2015; Walls *et al.,* 2021
Kongsberg	2005	Silver	342	16	Underground banqueting and concert hall (The Festsalen)	Banks *et al.* 2004; Walls *et al.,* 2021; Gzyl, and Skalny, 2025.
Poland						
Bytom	2017	Coal	Dewatering system	24 – 25	Pilot scale scheme for a housing development	Walls *et al.,* 2021
Czeladz	2011 - 13	Coal	Dewatering system (Pumps at 210 m bgl)	13 - 15	Demonstration project for CZOK offices	Walls *et al.,* 2021; Chudy, 2022
Sobieski Mine, Jaworzno	2015	Coal	500	15	Mine bathhouse	Walls *et al.,* 2021; Chudy, 2022
Russia						
Novoshakhtinsk, Rostov	2006	n.d.	50 – 150 390	12 – 13 18 – 23	Hospital, two schools and office buildings	Ramos *et al.,* 2015; Walls *et al.,* 2021
Osinnikovskaya	n.d.	Coal	n.d.	n.d.	Admin buildings of a mine	Walls *et al.,* 2021
Spain						
Asturias	2013	Coal	362	17-23	Research centre, student residence, and hospital	Jardon *et al.,* 2013; Ramos *et al.,* 2015; Loredo *et al.,* 2017; Walls *et al.,* 2021
United States						
Park Hills, Missouri	1995	Coal	133	14	Municipal Building	Watzlaf and Ackman, 2006; Hall *et al.,* 2011; Ramos *et al.,* 2015
Scranton, Pennsylvania	2010	Coal	120	13.8	University building	Ramos *et al.,* 2015

Abbreviations: NRW: North-Rhine Westphalia, m bgl: metres below ground level

2.3 Underground thermal energy storage

As well as providing a source of heat for district heating and cooling networks, abandoned mines have recently been investigated for use as underground thermal energy storage (UTES) (Bracke and Bussmann, 2015, Gluyas *et al.,* 2020). The following section will give a brief overview of the principles of thermal storage and describe forms of underground thermal storage before moving on to mine thermal energy storage.

As the electricity grid decarbonises, energy storage will become increasingly important due to the intermittent nature of renewable energy sources (Guelpa and Verda, 2019; Cabeza *et al.,* 2020; Gadd and Werner, 2021). Energy storage can increase the efficiency and reliability of an energy system and can reduce running costs, pollution, and carbon emissions (Sarbu and Sebarchievici, 2018). Energy can be stored as thermal energy (e.g. hot water tank), chemical energy (e.g. batteries), or potential energy (e.g. pumped hydro storage). Within thermal energy storage (TES) there is sensible or latent energy storage (Figure 2.3). Sensible energy is the most common form of thermal energy storage which uses the temperature change of the storage medium, which can be solid or liquid, to store energy (Figure 2.3). Latent thermal storage uses the energy stored when during a phase change of a material by melting (Hasnain, 1998) and is still in an early stage of its development (Guelpa and Verda, 2019).

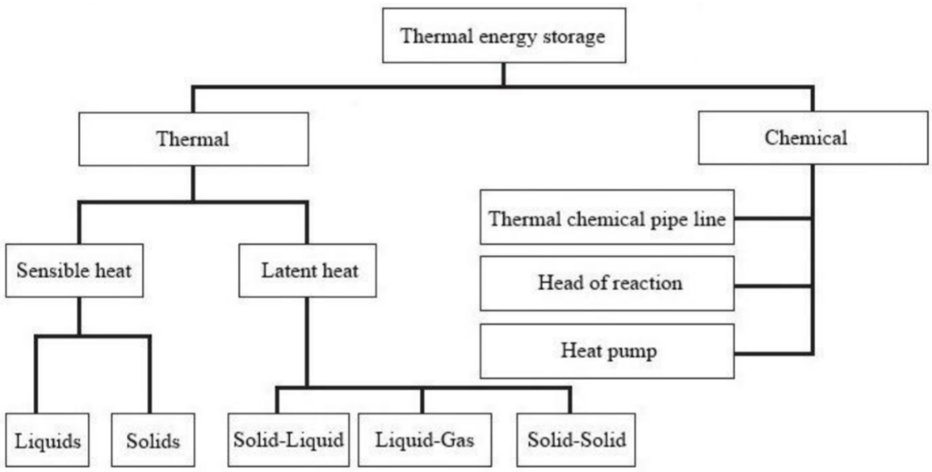

Figure 2.3: Diagram of types of solar thermal energy storage from Sarbu and Sebarchievici (2018).

Energy storage helps balance periods of over-supply with periods of over-demand. The temporal difference between energy production and energy use can range from seconds to seasons (Gadd and Werner, 2021) and is one of the main challenges facing the decarbonisation of heat (Fleuchaus *et al.*, 2018, Gluyas *et al.,* 2020). During the summer when most solar thermal energy is generated, there is less need for heating due to the higher outdoor temperatures. Conversely, when the temperature drops in winter, and heat is needed, less solar energy is received, meaning that less energy is produced by solar panels (vice versa for cooling demand (Guelpa and Verda, 2019)). Energy storage could also work on shorter time scales by storing heat generated in the daytime for nighttime use (Hasnain 1998). Energy storage also closes the temporal gap for energy sources that have intermittent generation, such as wind turbines which only generate electricity on windy days (Guelpa and Verda, 2019).

One way to store large amounts of thermal energy over long time periods is underground (Fleuchaus *et al.*, 2018, Gardiner *et al.*, 2023). Underground thermal stores use sensible heat storage and offer high storage capacity and high storage efficiency (Fleuchaus *et al.*, 2018). Mangold and Deschaintre (2015) state that for efficient inter-seasonal heat storage, a heat store needs to have a volume of at least 1000 m^3. The UK has a high potential for underground thermal energy storage (UTES) in geological resources such as aquifers, cave systems, and abandoned mines (Xu *et al.*, 2014, Gluyas *et al.*, 2020). Gluyas *et al.* (2020) estimated that there are 3968 billion tons of water underground across the UK, mostly in deep saline aquifers (3126 billion tons). Using this mass of water, it was estimated that large amounts of thermal energy, around 46,000 TWh, could be stored with small changes in temperature[4] (Gluyas *et al.*, 2020) Despite this, compared with European countries, underground thermal storage has been overlooked in the UK.

Manufactured systems for of storing heat underground include in tanks and pits, whilst on a smaller scale, they can still provide useful thermal storage (Dahash *et al.*, 2019). Aquifer, borehole, cavern, tank and pit thermal storage will each be briefly described below.

Aquifer thermal energy storage (ATES) refers to using aquifers to store heat energy and was first deployed in the 1960s in China to provide cooling (Figure 2.4, Nordell *et al.*, 2015, Gao *et al.*, 2017, Fleuchaus *et al.*, 2018). Aquifers are permeable geological units, generally sandstone, limestone, or gravels (Schmidt *et al.*, 2004), and provide a large-scale storage option and can also be used for geothermal energy production (Fleuchaus *et al.*, 2018, Brémaud *et al.*, 2023). Fleuchaus *et al.* (2018) provide a timeline of ATES development and comprehensive review of projects across the world, of which there are over 2800 operational projects.

Borehole thermal energy storage (BTES) uses an array of boreholes drilled to depths of between 30 – 100 metres below ground level (m bgl) (Figure 2.4, Schmidt *et al.*, 2004) to store thermal energy in the soil and rock. BTES is the most common form of underground thermal storage due to their small scale (Nordell, 2012). However, since the thermal energy is being

[4] 4,609 TWh with a 1°C temperature change, and 46,090 TWh of energy storage with a 10°C temperature change (Gluyas *et al.,* 2020).

stored in rock rather than water, BTES installations have to be between three and five times larger than a hot water to store the same amount of energy (Schmidt *et al.*, 2004).

Cavern thermal energy storage (CTES) refers to the use of water in caverns or other underground structures to provide sensible thermal energy storage (Nordell, 2012, Lee, 2013, Park *et al.*, 2014). Lee (2013) includes abandoned mines in a list of structures that could be considered for CTES projects, as well as tunnels, rock cavers, karst structures, and artificially constructed caverns. The first examples of this technology were developed in Sweden in the 1980s, firstly the Avesta reservoir with a capacity of 15,000 m^3 (Lee, 2013) secondly, the Lyckebo reservoir with a reservoir of 115,000 m^3 water at 90°C, which was able to store 5500 MWh of heat inter-seasonally (Nordell, 2012, Lee, 2013, Zhang *et al.*, 2024). Despite the large volume of storage available in caverns, its use is limited due to terrain constraints, large capital investment, and high operation costs. (Lee, 2013, Zhang *et al.,* 2024).

Tank thermal energy storage (TTES) schemes are the simplest form of thermal storage and use a large water tank, either above ground, partially buried or fully below the surface (Figure 2.4, Dahash *et al.*, 2019). Of the methods described here, this is the most independent from ground/geological conditions (Schmidt *et al.* 2004; Dahash *et al.* 2019). Similarly to TTES, pit thermal energy storage (PTES) are large pits in the ground that either store thermal energy in water or in a mix of gravel and water (Figure 2.4, Schmidt *et al.* 2018; Xiang *et al.* 2022).

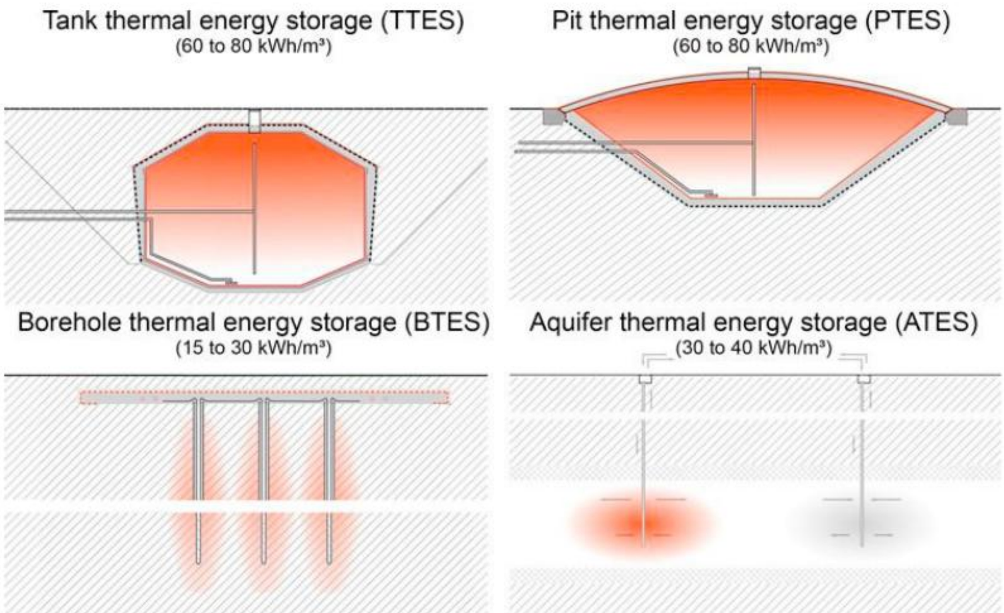

Figure 2.4: Underground thermal storage methods from Schmidt et al. (2018). Dahash *et al.* (2019) provide a useful comparison of the relative advantages and disadvantages of these four technologies.

2.3.1 Minewater Thermal Energy Storage

There are two ways in which thermal energy could be stored in an abandoned mine, either a flooded mineshaft or in the abandoned workings themselves ('anthropogenic aquifer'). Mine workings or shafts would essentially be acting as a giant hot water storage tank and could allow for inter-seasonal thermal storage (Bracke and Bussmann, 2015, Dassow *et al.,* 2024). This technology is often known as Mine Thermal Energy Storage (MTES), and there are a handful of pilot schemes operating in the Ruhr region of Germany (Hahn *et al.* 2018).

2.3.1.1 Prosper-Haniel Colliery, Bottrop, Germany

The Ruhr region was one of the Germany's main coal mining regions throughout the twentieth century with nearly 200 mines, employing 500,000 miners across the region (Urry, 2017). Prosper-Haniel colliery is located in the city of Bottrop between the cities of Essen to the west and Dortmund to the east and was once the largest employer in the city (Deutsche Welle, 2018). The mine opened in 1863 and ceased production in September 2018, marking the end of hard coal mining in Germany (Figure 2.5, Deutsche Welle, 2018). The closure of the mine was planned since 2007 (Deutsche Welle, 2018) as part of Bottrop moving towards being a centre for renewable energy generation. It became the first city in the Ruhr region to have a planned zone for wind energy, and in 2010 Bottrop was awarded the title of 'Innovation City' and currently gets 40% of its energy from renewable sources (Bracke and Bussmann, 2015; Urry, 2017).

In 2015, Prosper-Haniel colliery was still an active mine and Bracke and Bussman (2015) identified it as a potential seasonal heat storage reservoir, because repurposing it for thermal storage could be incorporated into the process of pit closure whilst the mine workings could still easily be accessed. Their concept was to store waste heat generated from fossil fuel plants, waste incineration, industrial processes, and unutilised heat from solar thermal plants in the mine during the summer, so that in the winter this heat can be directly used on the surface to heat buildings or circulated in a district heating network (Bracke and Bussmann 2015). The depth of the mine shaft at Prosper-Haniel was measured at -1159 m ordnance datum (OD) and the mined-out area was estimated to be 165 km^2, creating a large reservoir for the MTES. The undisturbed rock temperatures at depth were estimated to be between 30°C and 50°C (Bartels *et al.* 2018; Hahn *et al.* 2018; Kallesøe *et al.* 2019). Bartels *et al.* (2018) estimated that Prosper-Haniel would be flooded up to -687 m OD by 2035. Hahn *et al.* (2018) estimated that a conceptual high temperature mine thermal energy storage (HT-MTES) scheme at Prosper-Haniel could have a storage capacity of 12.8 gigawatt hours per annum (GWh/a) based on an injection of heat for six months and a storage volume of 252,000 m^3. Jagert *et al.* (2018) estimated a maximum temperature for injection of 90°C into the mine, as higher temperatures would lead to super-saturation of minerals in the mine water causing the pipes to clog up if an open loop system was used.

Prosper-Haniel was decommissioned at the end of 2018 (Figure 2.5, Deutsche Welle, 2018). The idea of using the now-abandoned mine for storage became a feasibility study known as GeoMTES (Kallesøe *et al.,* 2019), which had the aim of creating a technically and economically feasible model for an MTES. In 2021, as part of the decommissioning of the mine, the backfilling of the shafts with concrete at Prosper-Haniel had begun (Lugibihl, 2021, All News Press, 2021), meaning that it is now unlikely that there will be an MTES at Prosper-Haniel.

Figure 2.5: Miners at Prosper-Haniel hold the last lump of coal from the mine during a closing ceremony for the colliery on 21st December 2018, marking the end of hard coal mining in Germany (Associated Press, 2018).

2.3.1.2 Dannenbaum Colliery, Bochum, Germany

There are two MTES projects currently in development in Bochum, a city also in the Ruhr region of Germany, approximately 30 km to the east of Bottrop. Both projects in Bochum have received funding from the European Union Heatstore project which aims to accelerate the uptake of underground thermal energy storage (UTES) into the European energy system (Heatstore, 2022). There are six demonstration sites being developed for the EU Heatstore project in Switzerland, France, Belgium, The Netherlands, and Germany, each one focussing on a different type of UTES technology (Hamm *et al.* 2021). One of the projects in Bochum is based at Dannenbaum Colliery, which is located beneath the site of the former Opel car manufacturing plant in Bochum and was operational between 1859 and 1958 (Kallesøe *et al.* 2019). The concept of this project is to store unused heat from a combined heat and power (CHP) plant and solar panels, in the mine workings of Dannenbaum Colliery. The mine workings extend to a depth of -696 m OD where there is an estimated mine water temperature of 36°C. Currently the mine is flooded up to approximately -190 m OD (Kallesøe *et al.,* 2019). Two boreholes would be drilled into the workings, one would target Level 8 of the mine (-693 m OD), the planned heat reservoir. A second borehole would be drilled into shallower workings on Level 4 (-227 m OD) from which cool water will be pumped in the summer (Kallesøe *et al.,* 2019). On the surface, water will be heated to 90°C by solar energy and injected into and stored in the heat reservoir on Level 8 during summer, being pumped out again in the winter (Bücken *et al.* 2022).

Numerical and structural modelling on the mine layout to investigate the thermal and hydraulic effects of pumping water in and out of the mine, showed that the mine workings at Dannenbaum had both a high permeability and a large connectivity (Bücken *et al.* 2022). This was mainly due to the different mine working levels being connected by the mine shafts. This would create a 'thermal short circuit' between the heat reservoir on Level 8 and the cool storage area on Level 4, hot water from Level 8 would travel up the shaft and increase the temperature of the water on Level 4 and vice versa (Figure 2.6). As a result, Bücken *et al.* (2022) supposed that an effective heat storage would not be possible based on this borehole configuration.

Despite this thermal short circuit, in early 2022, Fraunhofer IEG (a research institution) and Stadtwerke Bochum (a local utility company) announced that they had successfully drilled two geothermal wells into the mine workings of Dannenbaum colliery, achieving depths of 340 m and 820 m below ground level (bgl), with the aim of extracting heat from the mine at a temperature of around 30°C (Richter *et al.,* 2022). This work forms part of the D2 Grids project, another EU funded projected focused on the development of 5th Generation District Heating and Cooling Networks (Kallesøe *et al.,* 2019; D2 Grids, 2023). Heat pumps will raise the temperature to approximately 45 °C to provide heating to the 'Mark 51°7 development', a development of office buildings (D2 Grids, 2023). Cooling will be provided by pumping water from a depth of 340 m at a temperature of 18°C (Richter *et al.,* 2022). Works are still ongoing at this project.

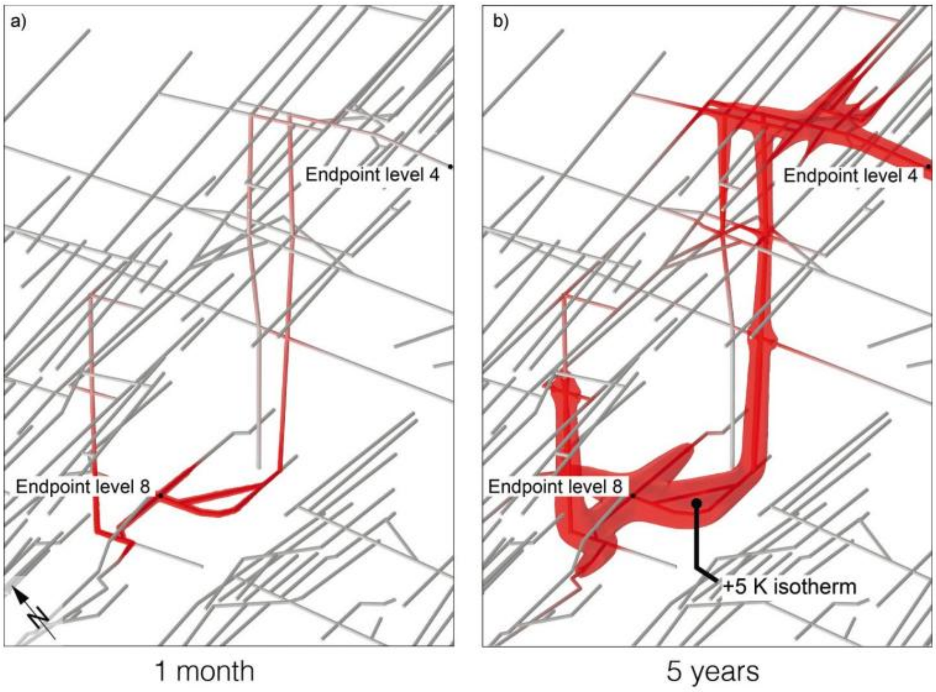

Figure 2.6: 3D rendering of the thermal short circuit between Level 4 and Level 8 of the Dannenbaum mine workings. Image from Bücken et al. (2022)

2.3.1.3 Markgraf II Colliery, Bochum, Germany

The second MTES project in Bochum is also part of the Heatstore project and aims to "create a technically and fully functional seasonal mine thermal energy storage pilot plant" (Koornneef *et al.,* 2019) for the storage of surplus heat from a concentrated solar plant (Heatstore, 2022). This project is based at The International Geothermal Centre (GZB) in Bochum beneath which lie the workings of Markgraf II Colliery (Hahn *et al.,* 2019; Koornneef *et al.,* 2019). Markgraf II is a much shallower colliery compared with Dannenbaum and Prosper-Haniel, with workings extending to approximately 75 m bgl and a minewater table sitting at approximately 21 m bgl (Hahn *et al.* 2019). Hahn *et al.* (2019) estimated that the volume of Markgraf II (not including shafts) is approximately 27,439 m^3 (based on a total coal production of 37,043 tons during its operational lifetime and a coal density of 1.35 g cm^{-3}). In the summer of 2020, three boreholes were drilled into the colliery to depths of between 29 m to 64 m bgl (Hamm *et al.* 2021). This is part of a two-year long operating and monitoring phase to collect data to inform future geothermal projects (Koornneef *et al.,* 2019). The first test operation was carried out during the winter of 2020/21 when 1,234 m^3 of mine water was brought to the surface and heated using solar thermal plant from 10.6°C to 45-50°C (equivalent to 50 MW_{th}). The heated water was then reinjected back into the mine at a depth of 64 m bgl, via an open loop system. The recovery efficiency of the heat over a three-month monitoring phase was 3.5%. It was found that rapid cooling of the reinjected heated mine water took place in the first day after reinjection with temperatures dropping by up to 40%, due to heat being lost to the surrounding rock mass (Hamm *et al.,* 2021).

In order to be effective, a minewater thermal storage system needs to have a large volume of mine water to use as a storage medium (Hahn *et al.,* 2018, Kallesøe *et al.,* 2019). Therefore, it is important to characterise the dimensions of any mine being considered for thermal storage. The next section is a review of the literature to collect data on thermal stores to determine the volumetric parameters that may be important for minewater storage schemes.

2.3.2 Underground thermal energy storage systematic review

A systematic literature review was carried out, based on the method described by Xiao & Watson (2019) with the purpose of collating parameters on thermal stores such as the dimensions, cost and the heat demand of the systems that they serve. The concept of storage volume will be explored further in Chapter 5 where methods of calculating the volume of mines will be investigated. Chapter 7 will compare the volume of mines with the volume of other thermal stores. First the scope of the literature is assessed, followed by an abstract review stage, followed by a full text review stage.

Google Scholar was used to assess the scope of the literature. Two search terms were used: ‘underground thermal energy storage’ and ‘underground thermal energy storage design’. To limit the number of results, the publication date range was set to between 2014 and 2024 and papers were selected from the first five pages of Google Scholar results based on their titles (Table 2.3). This literature search was carried out in mid-2024. Forty-three articles were selected based on their title from the first search term, and forty-one were selected from the second search term, which added the word ‘design’ into the search, which brought up different articles (Table 2.3). Care was taken to ensure there were no repeats between the two search terms, giving a total fifty-seven articles to include in the abstract review stage.

Table 2.3: Numbers of papers identified using two terms used in a search on Google Scholar. Papers were selected based on the relevance of their title. To limit the volume of literature, only the first five pages of google scholar were searched and the date range was set to 2014 – 2024.

	"Thermal energy storage" underground	*"Thermal energy storage" underground design*	Total articles
Selected from title	39	40	79
Repeated	-	22	22
Papers included	**39**	**18**	**57**

During the abstract review stage, the selected papers were classified into article type (e.g. review, experimental, modelling, see Table 2.4) and technology type. Following this, the full texts were reviewed, and parameters of thermal stores were collated (name, country, type, year, storage volume, and heat demand). Of the fifty-seven papers reviewed at the abstract review stage, the most common type of article was a review article (19 articles). The most common technology type (18 articles) was underground thermal energy storage (UTES) which encompasses all types of thermal energy storage. Of the individual technologies, borehole thermal energy storage (BTES) was the most common with 14 studies, followed by ATES with 5 studies. When the technology type was combined with the article type, the most common combination was UTES Modelling with 6 articles (Table 2.5). Following the abstract review stage, papers concerning borehole thermal energy storage (BTES) were discounted because the mechanism by which they store thermal energy through heating up the soil and rock around the boreholes rather than an underground body of water, so the data they contain will not be applicable to minewater thermal energy storage projects. As such, the fourteen BTES papers were excluded. Furthermore, during this stage, two of the full texts were not accessible as one was in Chinese with no English version, and one was from a conference and behind a paywall, reducing the total number of papers reviewed in the full text stage to forty-one.

Next, complete texts were read to collect specific parameters about specific schemes such as name, country, year, type, storage volume, and heat demand. Twenty-eight articles were found to contain no relevant data for specific thermal storage schemes. Data were collected from thirteen papers but only eleven contained data relevant to the rest of the review (i.e. some mentioned schemes but gave no locations or dates (e.g., Mahon *et al.* 2022) or were very small-scale storage solutions (e.g., <50m^3 TTES for a single building, Villasmil *et al.* 2019)).

Table 2.4: Definitions of the categories used for the type of articles. TES stands for thermal energy storage

Article Type	Definition
Review	Literature review articles
Experimental	Articles that detail experiments to do with TES
Modelling	Articles describing modelling of different types of TES
Case study	Articles describing a specific example of that type of TES
Regional study	Articles describing TES in a particular region or country

Table 2.5: Article type and technology type of the 57 papers in the abstract review stage. Please note N.S. stands for 'not specified', as in the type of technology was not specified in the article.									
Article type	**Technology**								**Total**
	UTES	**ATES**	**BTES**	**CTES**	**PTES**	**TTES**	**MTES**	**N.S.**	
Review	4	3	5	0	2	1	0	4	**19**
Experimental	3	0	3	0	0	0	0	0	**6**
Modelling	6	0	3	1	0	3	4	0	**17**
Regional study	5	1	1	0	0	0	0	0	**8**
Case study	0	2	2	1	1	1	4	0	**7**
Total	**18**	**6**	**14**	**2**	**3**	**5**	**5**	**4**	**57**

2.3.2.1 Data on storage volume

Across the selected eleven papers[5], there were data on storage volume for 45 projects across ten countries (Table 2.6). There was a wide range of storage volumes, ranging from 300 m^3 for both Egenhausen PTES and Ilmenau TTES in Germany, to a maximum volume of 200,000 m^3 for Vojens PTES[6], Denmark (Table 2.6). Figure 2.7 shows the distribution of storage volume across the 45 projects. Over half the projects have a volume of less than 10,000 m^3. The average storage volume was 27,413 m^3 (±46,976 m^3 SD) and the median was 5700 m^3. Germany was the country with the most schemes (19), but Denmark was the country with the highest total storage volume (532,500 m^3; Appendix 10.1).

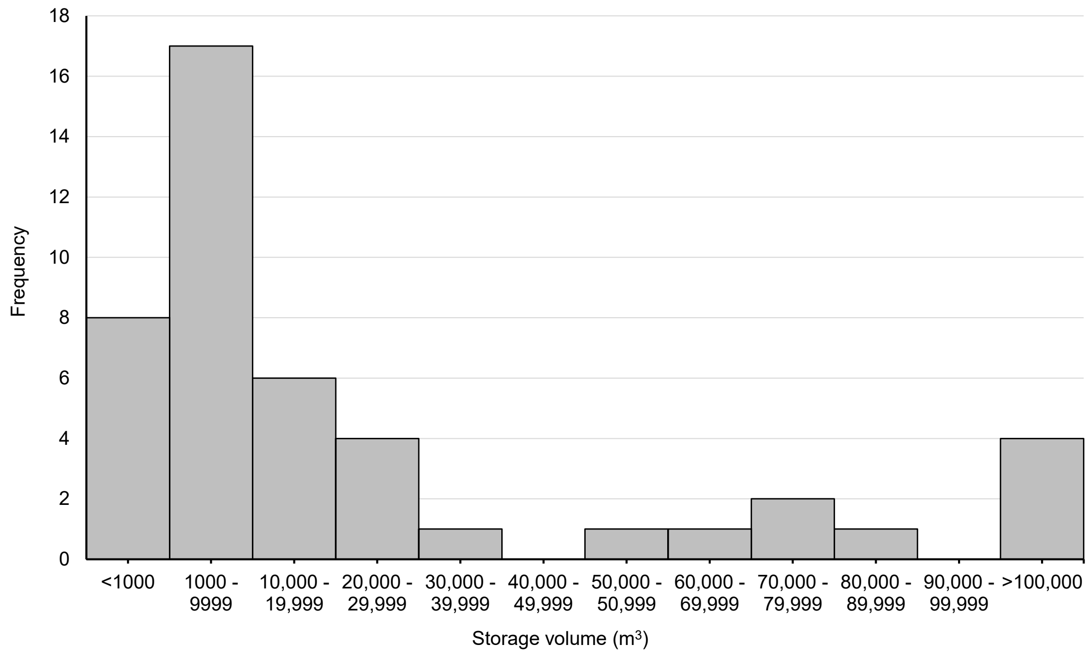

Figure 2.7: Histogram of storage volume in metres cubed (m^3) across the 45 projects.

[5] Bauer *et al.,* 2007, Guadalfajara *et al.,*2014, Park *et al.,* 2014, Xu *et al.,* 2014, Oosterbaan *et al.,* 2017, Rezaie, 2017, Alva *et al.,* 2018, Dahash *et al.,* 2019, Sarbu, 2021, Xiang *et al.,*2022, Zhang *et al.,* 2024.
[6] At the time of its construction, the Vojens scheme was the largest pit thermal store in the world and was excavated from a former sand pit (Epp, 2014, State of Green, 2014).

Table 2.6: The 45 thermal stores which had storage volume data reviewed in the full text review stage, sorted in alphabetical order by country. Schemes which also had data on both storage volume and heat demand are highlighted in bold.					
Name	**Storage Type**	**Year**	**Storage volume (m^3)**	**Heat demand (MWh a^{-1})**	**References**
Austria					
Linz	TTES	2004	34,500	n.d.	Dahash *et al.*, 2019
Salzberg North	TTES	2011	29,000	n.d.	Dahash *et al.*, 2019
Tisza	TTES	n.d.	50,000	n.d.	Dahash *et al.*, 2019
Vienna Simmering	TTES	2013	11,200	n.d.	Dahash *et al.*, 2019
China					
Langkazi	PTES - Water	2018	15,000	**37,300**	Xiang *et al.*, 2022
Denmark					
Dronninglund	PTES - Water	2014	60,000	**40,000**	Dahash *et al.*, 2019, Xiang *et al.*, 2022
Gram	PTES - Water	2015	122,000	**30,000**	Xiang *et al.*, 2022
Herlev	TTES	1991	3,000	**1,255**	Xu *et al.*, 2014, Xiang *et al.*, 2022
Hoerby	TTES	n.d.	500	n.d.	Xu *et al.*, 2014
Lyngby	PTES	2002	500	n.d.	Dahash *et al.*, 2019
Marstal	PTES - Water	2012	70,000	**32,000**	Guadalfajara *et al.*, 2014, Xu *et al.*, 2014, Alva *et al.*, 2018, Dahash *et al.*, 2019, Xiang *et al.*, 2022
Ottrupgard	PTES	1995	1,500	**425**	Guadalfajara *et al.*, 2014, Xu *et al.*, 2014, Xiang *et al.*, 2022
Rise	TTES	n.d.	5,000	n.d.	Xu *et al.*, 2014, Guadalfajara *et al.*, 2014
Toftlund	PTES - Water	2017	70,000	**28,000**	Xiang *et al.*, 2022
Vojens	PTES - Water	2015	200,000	**28,000**	Xiang *et al.*, 2022
Finland					
Kerava	PTES and BTES	1983	1,500	n.d.	Oosterbaan, 2017
Oulu	CTES	n.d.	190,000	n.d.	Zhang *et al.*, 2024
Germany					
Attenkirchen	TTES	2001	500	n.d.	Dahash *et al.*, 2019
Augsburg	PTES - Gravel & water	1997	6,500	n.d.	Guadalfajara *et al.*, 2014, Xu *et al.*, 2014, Dahash *et al.*, 2019, Xiang *et al.*, 2022
Chemnitz	PTES - Gravel & water	2000	8,000	**1,236**	Guadalfajara *et al.*, 2014, Xu *et al.*, 2014, Alva *et al.*, 2018, Dahash *et al.*, 2019, Xiang *et al.*, 2022
Crailsheim-Hirt	TTES	2006	480	n.d.	Dahash *et al.*, 2019
Egenhausen	PTES	1997	300	n.d.	Dahash *et al.*, 2019
Eggenstien	PTES - Gravel & water	2008	4,500	**1,400**	Guadalfajara *et al.*, 2014, Xu *et al.*, 2014, Dahash *et al.*, 2019, Xiang *et al.*, 2022
Friedrichshafen	TTES	1996	12,000	**4,106**	Bauer *et al.*, 2007, Guadalfajara *et al.*, 2014, Xu *et al.*, 2014, Alva *et al.*, 2018, Rezaie, 2017, Sarbu, 2018, Dahash *et al.*, 2019, Zhang *et al.*, 2024
Hamburg	TTES	1996	4,500	**1,610**	Guadalfajara *et al.*, 2014, Xu *et al.*, 2014, Dahash *et al.*, 2019
Hannover	TTES	2000	2,750	**694**	Xu *et al.*, 2014, Guadalfajara *et al.*, 2014, Dahash *et al.*, 2019

Ilmenau	TTES	1998	300	n.d.	Dahash *et al.*, 2019
Jena South	TTES	2011	13,000	n.d.	Dahash *et al.*, 2019
Julich	PTES - Water	1996	2,500	**590**	Xiang *et al.*, 2022
Munich	TTES	2007	5,700	**2,300**	Xu *et al.*, 2014, Guadalfajara *et al.*, 2014
Munich-Acker	TTES	2006	600	n.d.	Dahash *et al.*, 2019
Neckarsulm	BTES	1998	63,360	**3960**	Bauer *et al.*, 2007, Alva *et al.*, 2018
Rastatt	ATES	n.d.	23,000	**5,095**	Xu *et al.*, 2014
Rostock	ATES	2000	20,000	**497**	Bauer *et al.*, 2007, Guadalfajara *et al.*, 2014, Xu *et al.*, 2014, Alva *et al.*, 2018
Steinfurt	PTES - Gravel & water	1999	1,500	**325**	Bauer *et al.*, 2007, Guadalfajara *et al.*, 2014, Xu *et al.*, 2014, Xiang *et al.*, 2022
Stuttgart	PTES - Gravel & water	1985	1,050	**100**	Xu *et al.*, 2014, Xiang *et al.*, 2022
Ulm	TTES	2014	2,500	n.d.	Dahash *et al.*, 2019
Italy					
Calabria	TTES	n.d.	500	**30**	Xu *et al.*, 2014
South Korea					
KIGAM	CTES	n.d.	84,000	n.d.	Park, 2014
The Netherlands					
Diemen	TTES	2015	23,715	n.d.	Dahash *et al.*, 2019
Lisse	TTES	n.d.	1,000	n.d.	Xu *et al.*, 2014
Sweden					
Avesta	CTES	1980s	15,000	n.d.	Zhang *et al.*, 2024
Ingelstad	TTES	n.d.	5,000	n.d.	Xu *et al.*, 2014
Lambohov	PTES - Gravel & water	1980	10,000	**900**	Xu *et al.*, 2014, Xiang *et al.*, 2022
Lyckebo	CTES	1980s	120,000	**5,500**	Xu *et al.*, 2014, Zhang *et al.*, 2024
Switzerland					
Neuchatel	TTES	1997	1,000	n.d.	Guadalfajara *et al.*, 2014, Xu *et al.*, 2014, Zhang *et al.*, 2024

2.3.2.2 *Storage volume and heat demand data*

Of the 45 schemes that had data on storage, 23 also had data for annual heat demand in megawatt hours per year (MWh a^{-1}). The average heat demand across these 23 schemes was 9,785 MWh per year (± 14,115 MWh SD), the maximum heat demand was 40,000 MWh and the minimum was 30 MWh. The average volume was 33,152 m^3 (± 51,784 m^3 SD). Of the four different storage types represented, pit thermal energy storage (PTES) was the most common with 13 schemes and also has the highest annual average heat demand at 15,406 MWh (Appendix 10.2). Figure 2.8 compares the volume of the thermal stores with annual heat demand. The majority of stores have a volume of less than 10,000 m^3 and serve an annual heat demand of than less than 10,000 MWh a^{-1}. Three schemes, Gram and Vojens in Denmark and Lyckebo in Sweden, have a storage volume of over 100,000 m^3.

Figure 2.9 shows the annual heat demand as a function of the age of the scheme with bubble size indicating the volume of the thermal store in m^3. Thermal stores remained relatively small, less than 25,000 m^3 (with the exception of the Lyckebo CTES) and served heat demands of less than 10,000 MWh per year until the 2010s with the construction of the PTES systems in Denmark, which are all over 60,000 m^3 (with the exception of Langkazi PTES which is 15,000 m^3) and serving heat demands of over 25,000 MWh a^{-1}.

2.3.2.3 Cost of underground thermal energy storage

Only a handful of the reviewed papers listed the costs of different schemes, although Guadalfajara *et al.* (2014) had a list of the total capital cost of the storage aspect from 11 projects. Additional data on cost were found (Epp, 2014, State of Green, 2015, Leoni *et al.,* 2020, Herrmann *et al.,* 2026) to bring the total project with cost data to 14.

Nevertheless, from the limited volume of data available, the larger the volume of the store, the lower the cost per metre cubed of storage – i.e. small schemes are expensive for the amount of storage they provide (Figure 2.10) Schmidt *et al.* (2004) and Herrmann *et al.* (2026). For example, Hamburg TTES has a storage volume of 4,500 m^3 and has a cost per metre cubed of between €328.89 and €488.89 which is the highest of all the schemes (Figure 2.10). Whereas Friedrichshafen TTES has a much larger volume of 12,000 m^3 and a much lower cost per metre cubed of between €112.64 and €266.67 (Figure 2.10). The largest scheme in this review is Vojens PTES in Demark, reported to have cost between €4,016,640 (Epp, 2014) and € 4,450,000 (Herrmann *et al.*, 2026) to construct a pit store with a volume of 200,000 m^3. This translates to a cost per metre cubed of between €20.08 and €22.25 which is significantly lower than the smaller schemes (Figure 2.10).

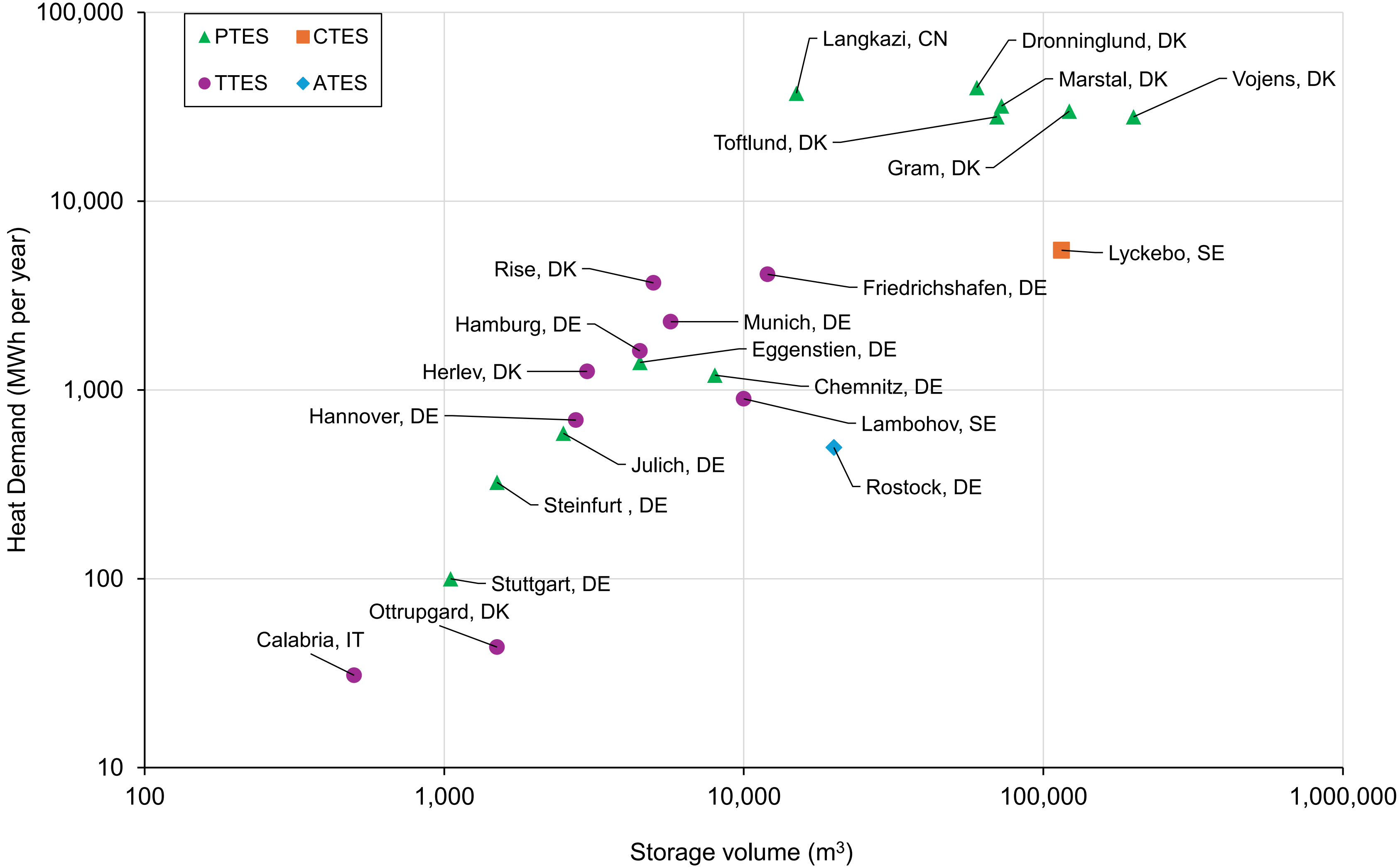

Figure 2.8: Volume against heat demand for the 23 projects which had data on both parameters. The data labels show the name of the scheme and the initials of its country, DE = Germany, DK = Denmark, SE = Sweden, CN =China, IT = Italy. Please note both axes use a logarithmic scale. Created using Excel.

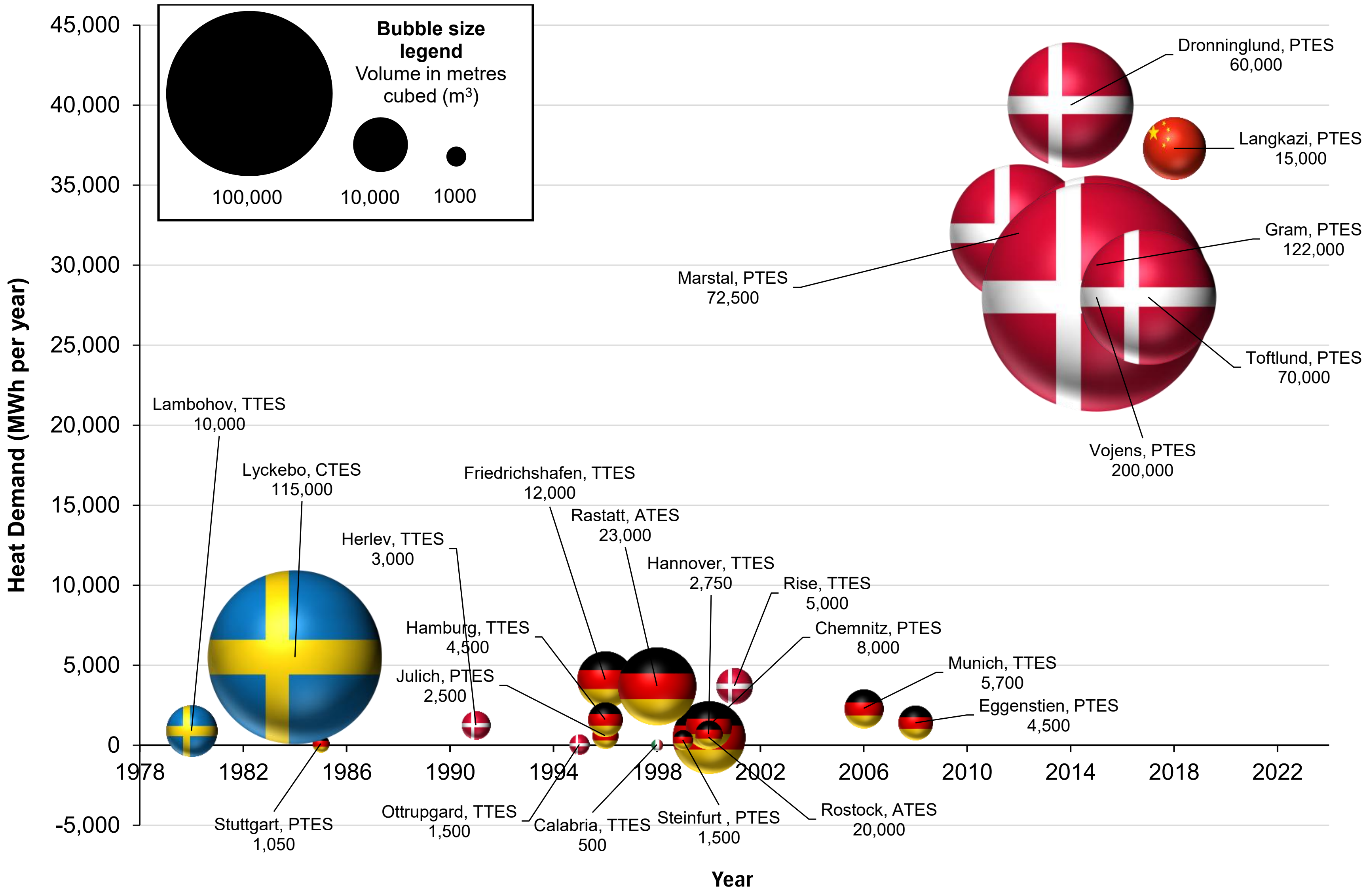

Figure 2.9: The volume, annual heat demand, and year of construction for thermal stores from the literature review. The size of the bubble represents the volume of the store in metres cubed (m3) and show the flag of the country the stores are located in. The data labels give the name of the thermal store, the type and the volume in m^3. Created using Excel.

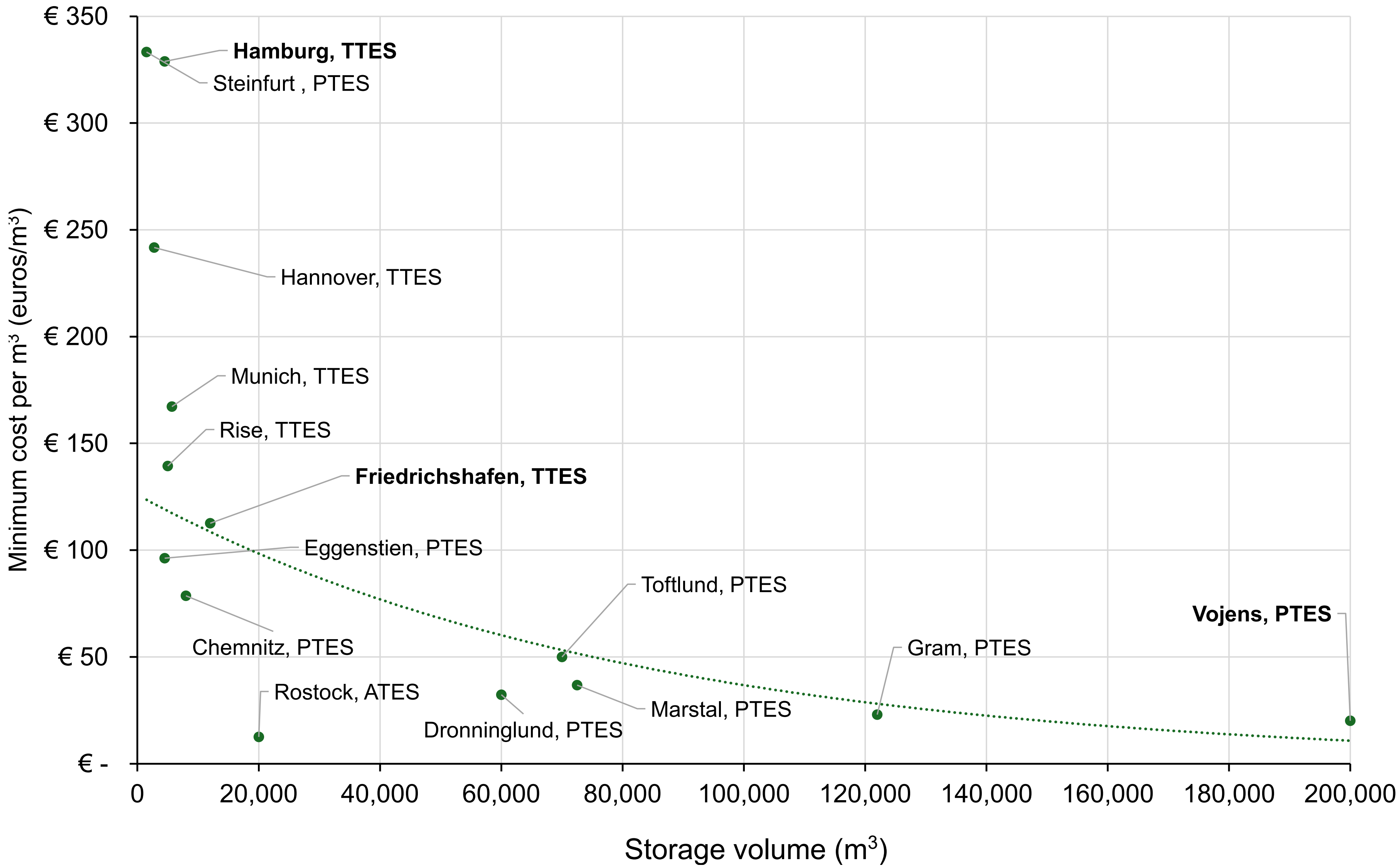

Figure 2.10: Volume against minimum cost per metre cubed (euros/m^3). The three schemes mentioned in the text are highlighted in bold. Data on costs from Guadalfajara et al. (2014), Epp (2014), State of Green (2015), Leoni et al. (2020), Herrmann et al. (2026).

2.4 Case study context: Scotland

Scotland was chosen the case study for this thesis for several reasons. It has a large amount of good quality spatial data, publicly available through the Spatial Hub (https://data.spatialhub.scot/). There is a wide spatial variability in the Scottish environment, ranging from urban city centres to remote mountains and islands. Scotland has a rich industrial history and as such there are a lot of historical data on coal mining to draw from. The following section provides an overview of the geology of the Scottish coalfields, a brief account of the history of coal mining in Scotland, and an analysis of Scottish coal outputs, followed by a review of Scottish housing stock and heating methods.

2.4.1 Geology of Scottish coalfield

The coalfields of Scotland were laid down during the Carboniferous approximately 300 million years ago. Ironstone also laid down in the same geological period (Dron, 1902). Coal is found across the Central Belt of Scotland in multiple basins stretching northeast from the Firth of Clyde in the west to the beyond the Firth of Forth in the east (Figure 2.11, Dron, 1902). Most coals found in Scotland are bituminous and have a high volatile matter content, but range from “dirty, smoky” bituminous to “hard, clean, smokeless, anthracites” (Hyde, 1987).

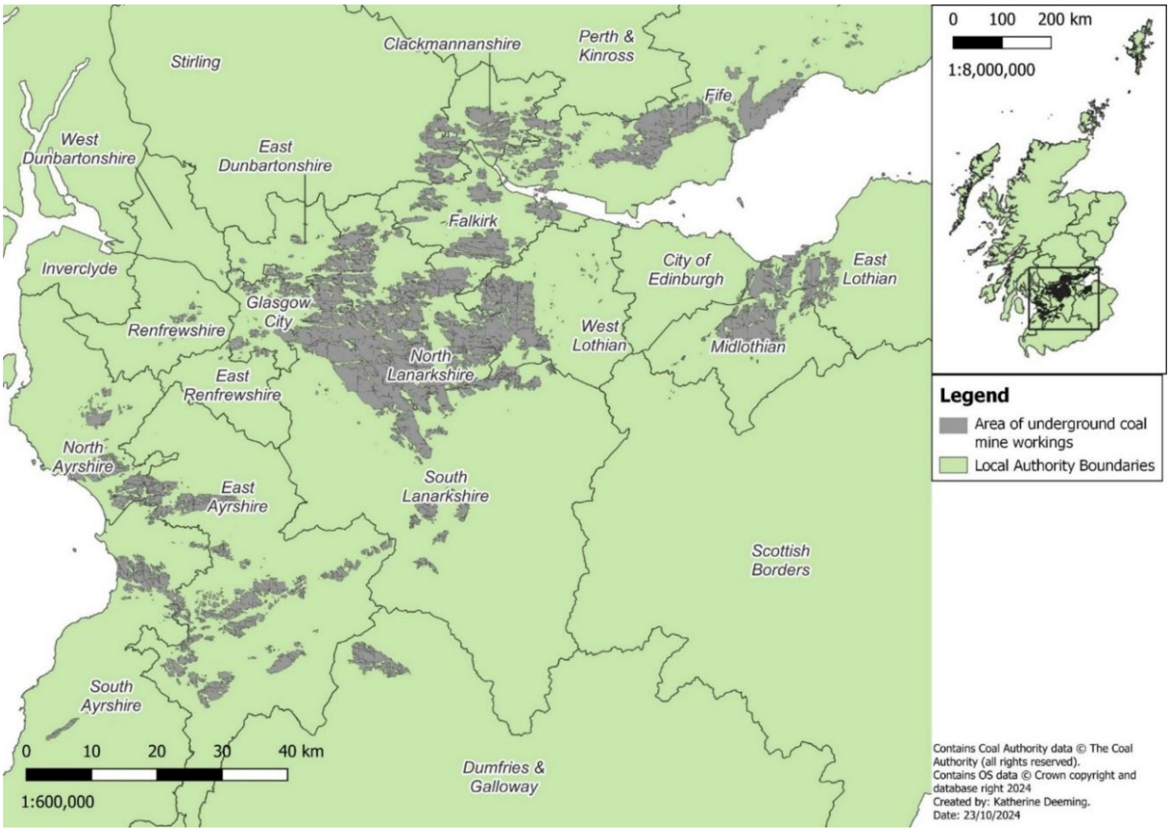

Figure 2.11: Area of underground coal mine workings across the Central Belt of Scotland. Contains underground workings data from the MRA (2023c) and boundary line data from Ordnance Survey (2024a).

2.4.2 History of coal mining in Scotland

In order to implement successful minewater heating or storage schemes an understanding of the history of coal mining and the coal mining communities of the area is needed to ensure that any future developments are handled in a manner that is sensitive to the history of the location, and past and present residents of the location (Roberts *et al.,* 2023).

Coal has been burned in Britain for over 2,000 years, starting with the Romans who used it in furnaces, forts, and for a perpetual fire at Minerva's shrine in Bath (Hyde, 1987, Freese, 2006, pg. 15, NCM, 2023). Early Scottish coal mining started around the Firth of Forth where coal seams were exposed along the coastline (Duncan, 2005, HES, 2025). During this time coal was known as 'sea-coal' either because it was picked from shorelines, or because it was transported by sea to be sold in cities in England (Duncan, 2005, Freese, 2006). The earliest estimate of coal output was from Hyde (1987) who estimated that in 1500, approximately 40,000 tons of coal were being produced in Scotland. Duncan (2005) estimated that annual output had increased five-fold to 225,000 tons by 1700. Of that, over two thirds (150,000 tons a year) were sold to households for domestic burning (Duncan, 2005). The smoke produced by all the coal fires in Edinburgh led to the city acquiring the nickname 'Auld Reekie' (Hyde, 1987, Duncan, 2005).

The co-location of ironstone and coal proved important for regions of Scotland during the industrial revolution, particularly in Central Scotland. Iron smelting used a vast quantity of coal and having a supply nearby was crucial for many early ironworks (Duncan, 2005). The first ironworks opened in 1760 at Carron near Falkirk and remained the only ironworks in Scotland for the next 20 years (Duncan, 2005). Gartsherrie Ironworks in North Lanarkshire, opened 1830 (Figure 2.12).

By 1900 coal production exceeded 33 million tons per year (Figure 2.14, Dron, 1902, Moore, 1950), and coal had become ubiquitous throughout society and powered the industrial revolution in factories, railways, steamships, gas works as well as households (Turnheim and Geels, 2012). Coal production reached its peak in 1913, with a total of 42,456,516 tons of coal mined in Scotland (Moore 1950), which accounted for 14.5% of the total UK coal production that year[7] (Figure 2.14). During this time, coal mining provided 10% of all jobs for the male population, making it the largest employer of industrial labour in the UK (Turnheim and Geels 2012).

[7] Coal production in the UK, was 292 million tons in 1913 (DESNZ, 2025b).

Figure 2.12: Gartsherrie by Night (1853) by Caleb Robert Stanley (1795 – 1868), from North Lanarkshire Council Museums (n.d.)

The coal industry in Great Britain was nationalised on 1st January 1947, and collieries were brought under government control in the form of the National Coal Board (NCB; Moore,1950, Duncan, 2005, British Pathé, 2014). In Scotland, the Scottish Divisional Coal Board acquired 269 collieries, which had previously been operated by over 120 companies (Moore, 1950). Post nationalisation surveys found that more than half of the collieries acquired by the Scottish Divisional Coal Board were not viable as they were either severely dilapidated or the workable coal measures were nearing exhaustion (Duncan, 2005). This led to over 100 collieries being listed for closure or rationalisation before 1965 (Duncan, 2005). To account for this, nine modern 'super pits' were planned (including Killoch, Chapter 5) with the aim of reaching coal reserves at depths of 700 – 900 m bgl (Duncan, 2005).

Throughout the latter half of the twentieth century, the Scottish coal industry faced widespread decline increasing competition from petroleum and nuclear energy (Gibbs, 2021). In the face of increasing closures by March 1984, *"a majority of Scotland's miners were locked out [or] on strike"* (Gildea, 2023, pg. 40), a month before their English counterparts (Gildea, 2023). Decline continued after the strike through the 1980s and 1990s. Deep mined coal production in Scotland ceased with the closure of Longannet Colliery in Fife following a flood in March 2002, when 17 million gallons of water flooded the underground workings (Oglethorpe, 2006, Gibbs, 2021). This closure marked the end of an industry that had been crucial in Scotland for centuries (Figure 2.13).

Figure 2.13: The last five miners back on the surface after the last shift at Longannet Colliery. From left to right: Stewart Steele, Kevin Skelton, Lachie Farries, Kenneth Nicholson and Stewart Nicholson (The Scotsman, 2016)

2.4.3 Coal production in Scotland

To understand the scale of minewater thermal resources in Scotland, we need to understand the volume of mining void and how and when it was created. Coal production data from the government is for the whole UK (DESNZ, 2024b) so it is difficult to get a clear picture of how much coal was mined in Scotland and there for how much void was left behind. Whilst not as comprehensive as the DESNZ (2024b) data, which has data for every year from 1912 to 2023, coal output from multiple sources have been collated and plotted with UK coal production data from DESNZ (2024b) in Figure 2.14. The opening and closing dates of Scottish collieries (Oglethorpe, 2006) been plotted in Figure 2.15.

On average, Scotland produced for 11% of total UK coal production, ranging from 16% in 1900 to 2% in 1988. Using these production statistics, the total amount of coal mined in Scotland between 1854 and 1988 can be estimated as being between 2.68 billion and 2.97 billion imperial tons, which gives an average annual output of between 2.7 billion and 3 billion metric tons. This will be expanded on in Chapter 5 where methods of estimating mine volumes, these values of coal production will be used to compare the methods of estimating volume for the whole of Scotland.

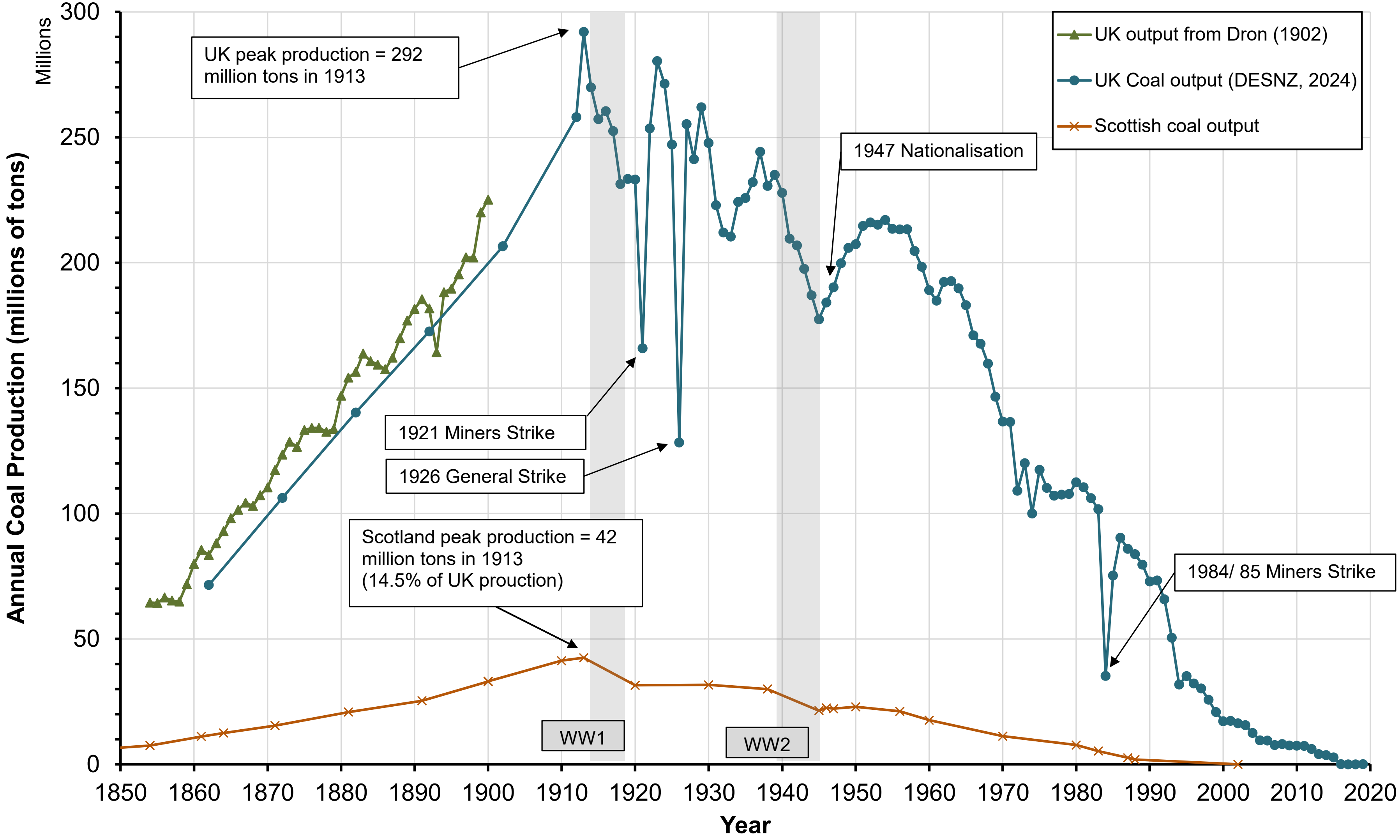

Figure 2.14: Coal production in the UK and Scotland from 1850 to 2020. Contains data from Dron (1902) and DESNZ (2024) for UK data and from Scotland data from Dron, (1902), Moore, (1950), Hyde, (1987), Halliday, (1990), Duncan, (2005).

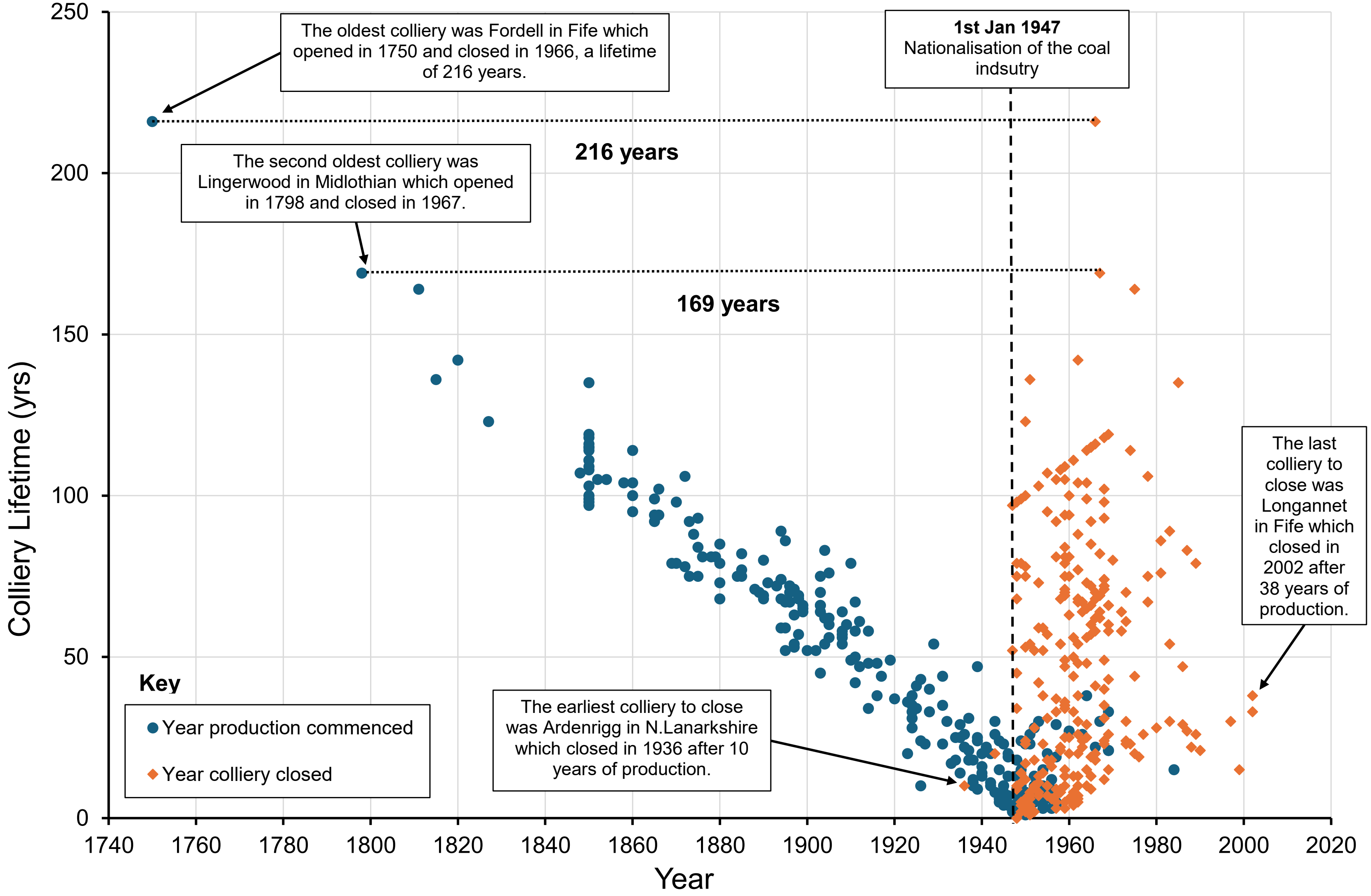

Figure 2.15: Year of opening (blue) or closing (orange) versus colliery lifetime. Contains data from Oglethorpe (2006).

2.4.4 Scottish housing stock

To better understand the scale of the decarbonisation challenge in Scotland and whether minewater heating and storage schemes can contribute, it is important to be aware of the makeup of the housing stock and how homes are currently being heated. The Scottish Housing Condition Survey (SHCS) is the largest housing research project in Scotland. It is a national housing survey first carried out in 1991 and every year since 2003 (Piddington *et al.,* 2020). It was integrated into the Scottish Housing Survey in 2012 and provides data on the physical condition of dwellings in Scotland and the experiences of their residents (Scottish Government, 2024b). These data are from the 2022 survey which was published in 2024 (Scottish Government, 2024b and 2024c).

2.4.4.1 Type of houses

Scotland has a higher proportion of flats in its housing stock than the rest of the UK; 36% of homes in Scotland are flats, compared with the UK average of 21%. (Piddington *et al.,* 2020). Most of these flats (64%) are in the form of tenements that were built as workers housing during the industrial revolution (Piddington *et al.,* 2020). Approximately 185,000 tenements were constructed before 1919 (7% of total Scottish housing stock). A comparable number of tenement flats (182,000) were constructed in Scotland after 1982 (Figure 2.16). In the post-war period (1945 – 1964) more terraced houses were built than other types of homes (Figure 2.16). The majority of dwellings in Scotland are in urban areas (83% - 2.13 million households) with 423,000 households (17%) found in rural areas. The most common type of dwelling in urban areas is the tenement flat (Figure 2.17) with 577,000 tenements accounting for 27% of all urban housing (and 97% of all tenement flats in Scotland). In rural areas, the most common housing type is detached houses (212,000), which account for 50% of all rural homes. As such, on average rural properties are 32% larger than urban dwellings (based on internal floor area, Scottish Government, 2024b).

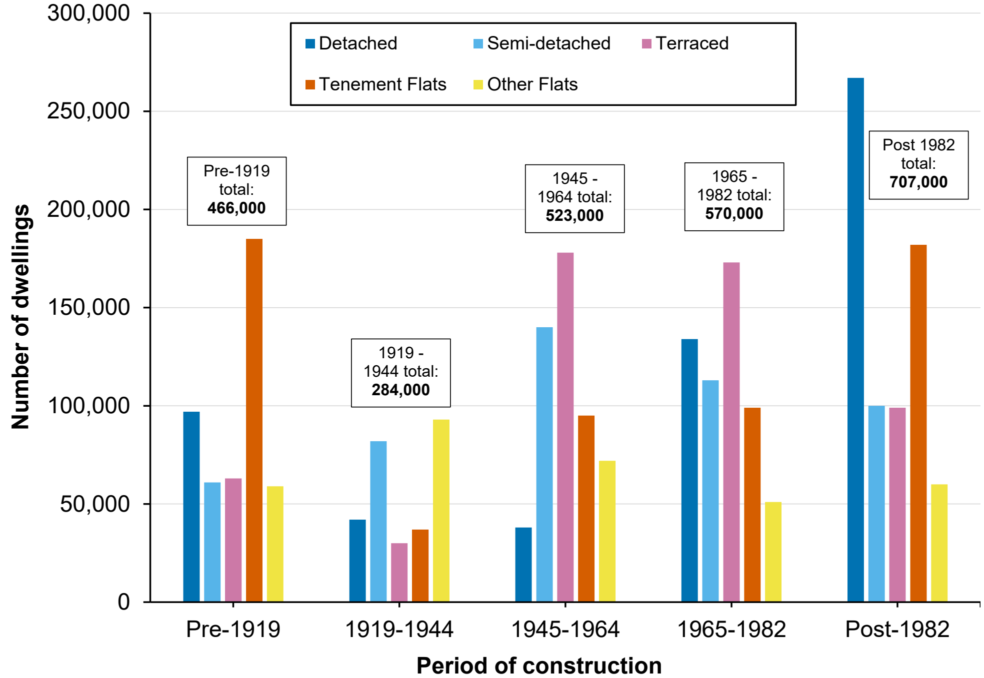

Figure 2.16: The number of all occupied dwellings in Scotland (n = 2,550,000) split by age and type of building. The text boxes above each age group show the total number of homes built during that period. Contains data from Scottish Government (2024c).

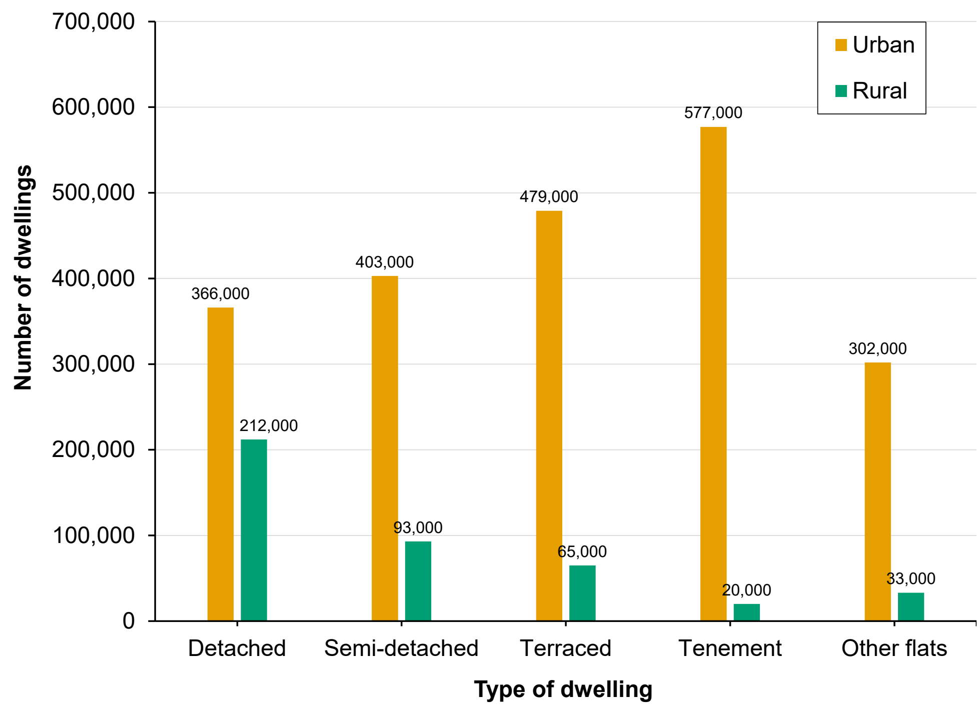

Figure 2.17: The number of dwellings of each type, split between urban (n = 2,127,000) and rural (n = 423,000). Contains data from Scottish Government (2024c).

2.4.4.2 Heating system fuel and type

Figure 2.18 shows the main fuel type used for heating for all dwellings across Scotland. Mains gas is 81% of Scottish homes, around 2 million properties, electricity is used by 11%, and 5% use oil heating (Figure 2.18). According to the SHCS, 18% of dwellings in Scotland are outside the coverage of the mains gas grid, or "off grid". This means they are further than the *"usual maximum distance for standard domestic connection",* which is 63 metres. In rural areas, the majority of dwellings are off grid (65%) whereas in urban areas this is a minority (9%) of homes (Scottish Government, 2024b). As such, the heating fuel type in rural areas is much more varied (Figure 2.19b). Most homes (2,254,000 or 88%) use a boiler for heating, either fuelled powered by mains gas, oil, LPG, or potentially biomass (Figure 2.20). Storage heaters heat 5.7% of homes, warm air systems, and room heaters account for 3.1% of dwellings and 1.3% of dwellings use heat pumps (Figure 2.20). The SHCS statistics do not make clear what fuel the boilers are using. In 2022, the SHCS found that 98% of boilers in Scotland had been installed since 1998 (Scottish Government, 2024b).

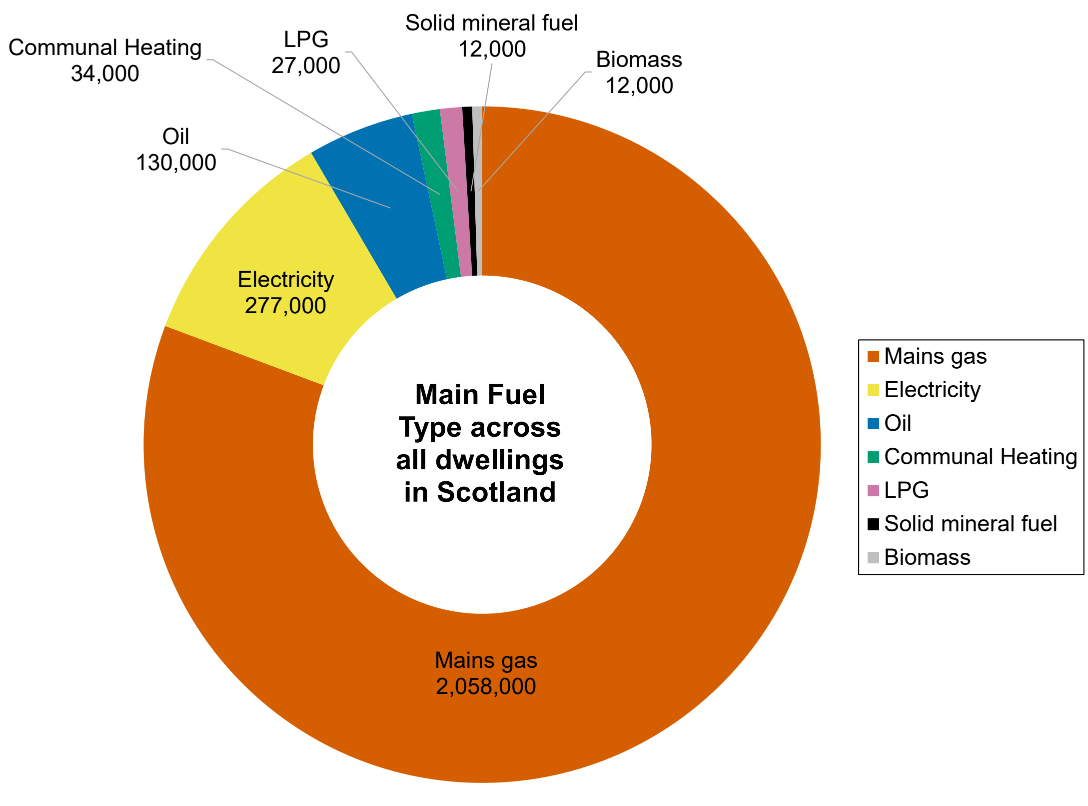

Figure 2.18: Main Fuel Type for heating across all dwellings in Scotland in 2022 (n = 2,550,000). LPG stands for Liquid Petroleum Gas. Contains data from Scottish Government (2024c).

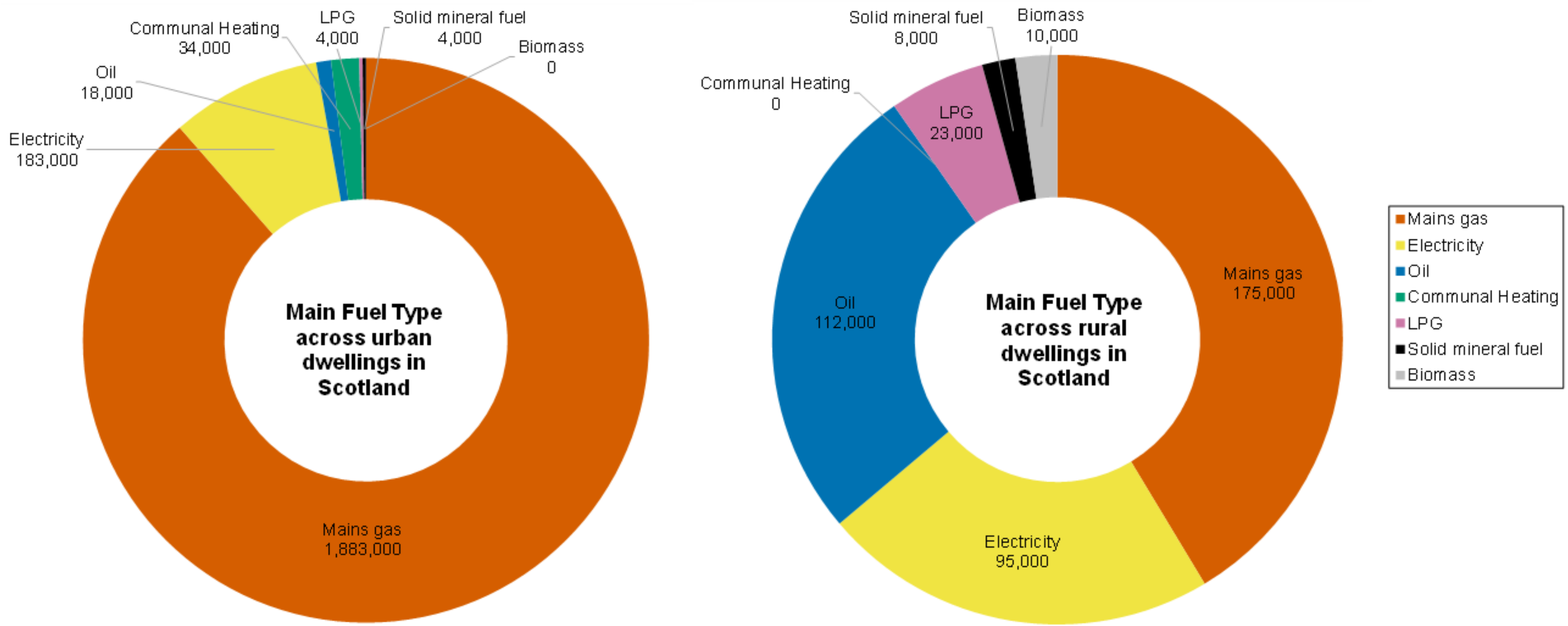

Figure 2.19: A comparison of the main fuel type used in a) urban dwellings (n = 2,126,000) and b) rural dwellings (n = 423,000) across Scotland in 2022. Contains data from Scottish Government (2024c).

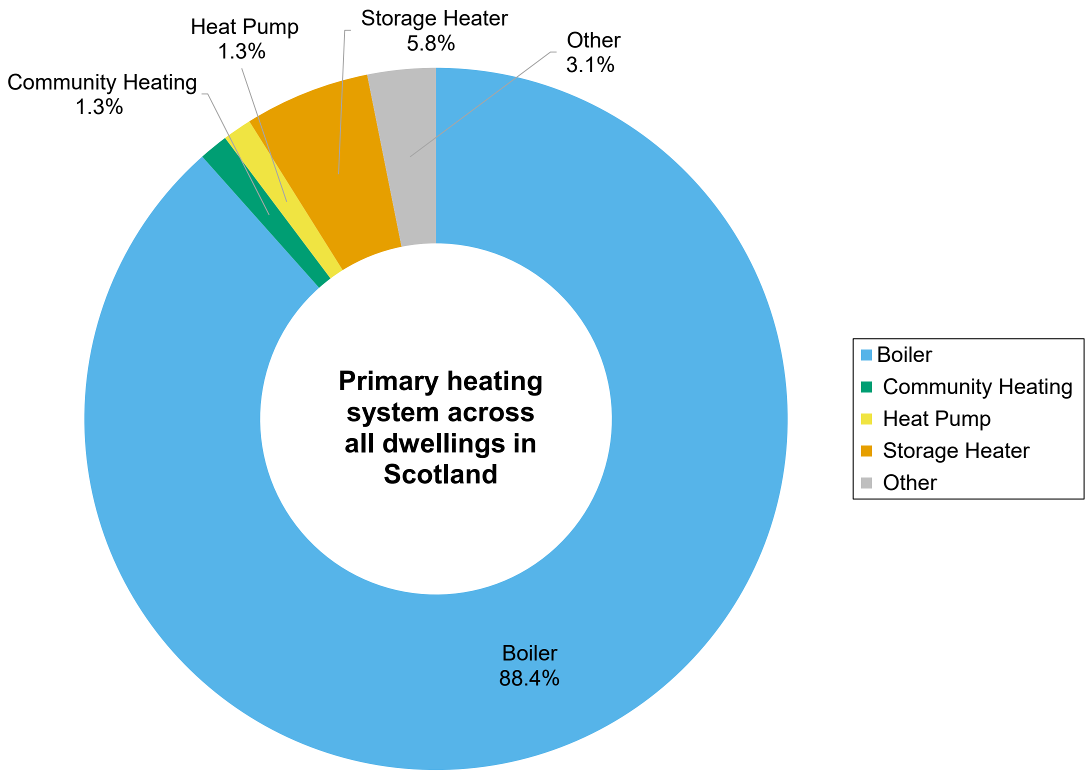

Figure 2.20: Primary heating system across all dwellings in Scotland in 2022 (n = 2,549,000). Please note boiler includes gas, oil, LPG, and biomass powered boilers. The 'Other' category includes heating systems such as warm air systems and room heaters. Contains data from Scottish Government (2024c).

2.4.4.3 Fuel poverty

Fuel poverty was defined by the Scottish Government in the Fuel Poverty (Targets, Definition and Strategy) (Scotland) Act (2019) as when a household spends more than 10% of their income (after housing costs) on fuel costs, and for extreme fuel poverty it is 20% of a household's income. Figure 2.21 compares the number of households in Scotland experiencing fuel poverty and extreme fuel poverty between 2019 and 2022, following the pandemic and energy crisis. Households in fuel poverty increased from 613,000 in 2019 (25% of all households), to 791,000 in 2022 (31% of all households), and of those, the number in extreme fuel poverty went from 311,000 households in 2019 (12.4% of all households), to 472,000 households in 2022 (18.5% of all households). There was also an increase in the fuel poverty gap, which is the amount of money it would take to move a household out of fuel poverty. In 2019 the median fuel poverty gap was £750, in 2022 it has increased to £1,240.

Decarbonising heating if not carefully managed could lead to an increase in those experiencing fuel poverty, due to the difference in price between gas and electricity in the UK (electricity currently 3.9 times the price of gas (Shepeard *et al.*, 2024). The type of fuel used to heat a home therefore makes a significant impact on whether that household is in fuel poverty or not; 46% of households that use electricity for heating were in fuel poverty, compared with 29% for gas, and 29% for oil (Scottish Government, 2024b). Additionally, households with electric heating were more likely to report that their heating does not always keep them warm in winter, compared with households heated by gas, (37% of electric heated households compared with 19% for gas; Scottish Government, 2024b). Households heated by mains gas had a fuel poverty rate of 31%, and those not on the gas grid had a rate of 30% (Scottish Government, 2024b).

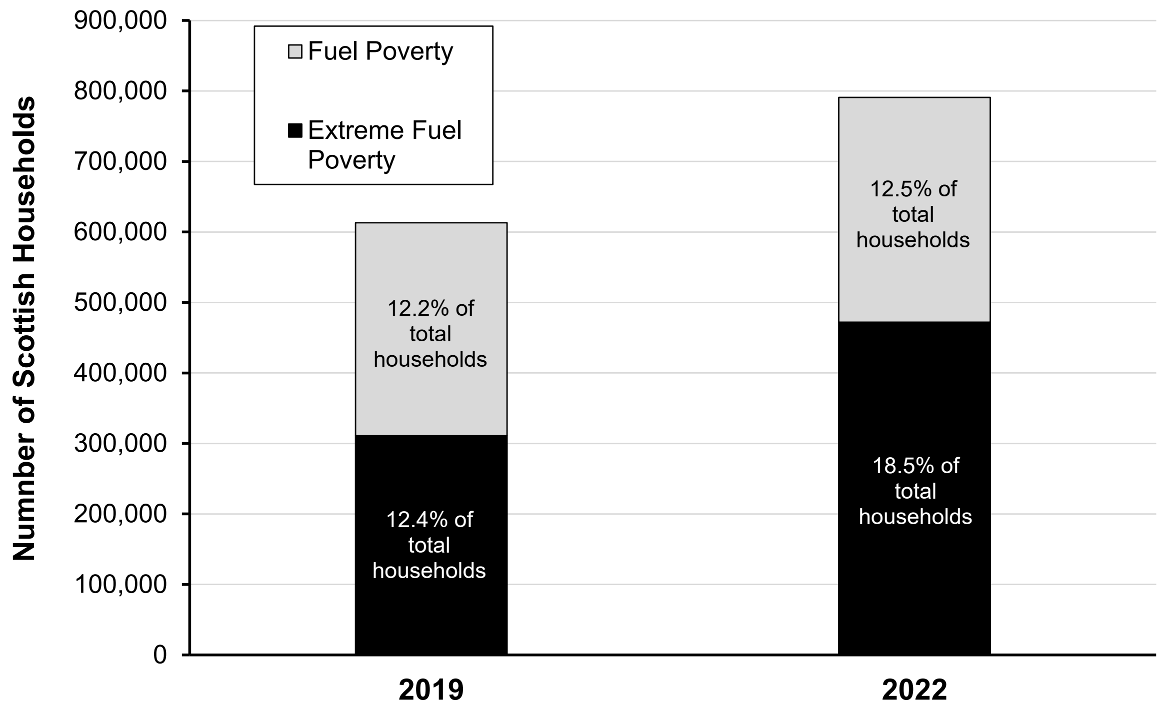

Figure 2.21: Comparison between rates of fuel poverty and extreme fuel poverty in Scotland in 2019 and 2022. Contains data from Scottish Government (2024c).

2.5 Research gap

This literature review shows that there is an opportunity to consider the spatial aspects of minewater thermal resources in the wider context of heat decarbonisation. It is crucial that the decarbonisation of heat is underpinned by spatial data analysis as heat is an inherently spatial resource. There is a need to better understand whether there is a practical and meaningful co-location between minewater thermal resources and heat demand, and to quantify how much of a role, if any, they might play in the decarbonisation of heat in Scotland.

Minewater projects will not happen in isolation, they need to be considered among the full range of other heat decarbonisation options and strategies and consider practicalities for local communities or stakeholders who will be involved in the development of these schemes. Currently there has been little research into assessing minewater thermal resources in their geographical, historical, social contexts (Roberts *et al.*, 2023).

Scotland will be used as a case study for the aforementioned reasons. Scottish Government has taken a regional approach to heat decarbonisation through the LHEES programme. Therefore, it is important to consider the minewater resources within the context of this policy and provide useful information that local authorities can use. A strategic and coordinated approach will be needed to move away from gas boilers over the next 20 years, in order to reach the Scottish Government's target of net zero by 2045.

3. CHAPTER 3: Nurturing a new industry rooted in geoscience: Stakeholder insights on minewater thermal in Scotland.

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Author contributions

KBD: Conceptualisation, methodology, participant recruitment, conducting the interviews, transcription, and formal analysis, writing the original manuscript, visualisation. ZKS: Conceptualisation, funding acquisition and participant recruitment, supervision, reviewing and editing manuscript. JD: Supervision, reviewing and editing manuscript. JJR: Supervision, reviewing and editing manuscript. All authors have read and agreed to the published version of the manuscript.

Abstract

Heat decarbonisation is crucial for climate action and the transition to a sustainable society. Abandoned, flooded mines can be used to provide low-carbon heating and cooling for buildings or as thermal energy storage for district heating networks (‘minewater thermal resources’). Due to the capital-intensive nature of the infrastructure required for minewater thermal, its use should be considered early in project development. Developers therefore need to be aware of the full range of low-carbon heating solutions to implement the most sustainable solutions. Through interviews with twelve key stakeholders in Scotland, this study aims to determine the level of awareness of this technology among stakeholders who require heat for their developments, and stakeholders who would be involved in the development or construction of such schemes. Our findings have implications for how the geoscience community could aid the development of a minewater thermal industry. Stakeholders perceived a range of advantages of minewater, including use as thermal storage and the co-location of minewater resources with heat demand. Perceived disadvantages included the high capital cost and pre-construction risks associated with determining the feasibility minewater resources. Building trust and confidence in minewater thermal technology was identified as a key factor for success. Issues relevant for low-carbon heat in general were also raised including, high retail cost of electricity, skills gaps and labour shortages. Geoscientists can identify prospective minewater resources and assess the risks associated with exploration, development and operation of that resource, contributing to building confidence and reducing up-front capital costs. Given the multidisciplinary nature of the heat decarbonisation challenge, geoscientists must be able to communicate clearly and transparently about the science underpinning resource estimates and risk mitigation measures. For minewater thermal projects to succeed, geoscientists must be equipped with skills, knowledge and understanding to embrace these wider roles in nurturing this nascent industry.

3.1 Introduction

The decarbonisation of heat in buildings is crucial to meet global climate change mitigation targets and move towards a more sustainable society. In 2022, space heating alone was responsible for 3 billion tonnes CO_2e globally (8% of global greenhouse gas emissions) (IEA, 2023a). Thermal energy differs from electrical energy and fossil fuels in that it cannot be transmitted or transported long distances due to heat losses (Ma *et al.,* 2009; Jung *et al.,* 2022) and must be consumed close to where it has been generated. Heat generated from sources such as waste industrial heat or geothermal heat can be distributed by local or district heating networks (Di Lucia and Ericsson, 2014; Werner 2017) and can offer an alternative to high-carbon heat from fossil fuel combustion as well as increasing energy security (Altermatt *et al.,* 2023). The disparity in time between when heat is generated and when it is required is another key difference between thermal energy and other energy forms (Guelpa and Verda, 2019). For example, heat can be generated in excess in the summer by solar thermal plants, but it is not in high demand until the winter months, when less energy is generated by solar thermal (Schmidt *et al.,* 2004). Therefore, the inter-seasonal storage of heat energy to ensure that thermal energy is not wasted will be a crucial factor for decarbonising heat (Gadd and Werner, 2021). Due to these spatial and temporal constraints, low carbon heat needs to be generated close to the end-users of the heat. This is a very different way of heating residential buildings for countries such as the United Kingdom (UK) or the Netherlands, both of which have over 80% of residential buildings connected to a centralised natural gas grid (Kerr and Winskel, 2021). In the UK specifically, 85% of homes are connected to the mains gas grid for heating (Kerr and Winskel, 2021) and heat (both domestic and industrial) is the largest contributor to the UK's greenhouse gas emissions, accounting for 37% of total emissions in 2017 (BEIS, 2018).

Geological resources can aid heat decarbonisation (Stephenson *et al.,* 2019; Gardiner *et al.,* 2023). Deep geothermal can provide electricity and high enthalpy heat (Younger *et al.,* 2016; Gluyas *et al.,* 2018; Reinecker *et al.,* 2021) and shallow geothermal resources can provide low enthalpy heat (Schiel *et al.,* 2016; Boon *et al.,* 2019). Additionally, thermal energy can be also stored in the subsurface, either in aquifers, pits, or abandoned mines (Fleuchaus *et al.,* 2018; Hahn *et al.,* 2018a; Kallesøe *et al.,* 2019; Li *et al.,* 2022) and ground source heat pumps can heat buildings more efficiently than most fossil fuel heating systems (Safa *et al.,* 2015; Aditya *et al.,* 2020). However, despite the wide range of geothermal resources in the UK (Downing and Gray, 1986; Busby, 2010), adoption of geothermal energy has been slow (Batchelor *et al.*, 2021; Bremaud *et al.,* in review). Geoscience knowledge is required in many aspects of the energy transition from geothermal energy production to mining critical metals (Gardiner *et al.,* 2023). For projects using geological resources to provide low carbon heat, the expertise of geoscientists will need to be combined with expertise from other sectors such as the district heating, housing, and construction industries.

In this study, we aimed to investigate the awareness of minewater thermal resources amongst key stakeholders that would be involved in decarbonising heat and housing in Scotland, with a view to understanding where they see the barriers and enablers to the adoption of minewater thermal resources. We then see how these findings could be applied to the geoscience community and how they can help the development of this new industry.

3.1.1 Minewater thermal resources

When a subsurface mine is closed and abandoned, the mines often become naturally flooded with groundwater that is warmed by the Earth's geothermal heat. Heat can be extracted from ambient water using heat exchangers and boosted by heat pumps powered by electricity and can provide a source of low-carbon heat and hot water for domestic or commercial use (Banks *et al.,* 2004; Watzlaf and Ackman, 2006; Banks, 2012; Bailey *et al.,* 2013; Ramos *et al.,* 2015; Walls *et al.,* 2021). Using minewater as a source of heat for heating and cooling systems is typically known as minewater geothermal and there are several minewater geothermal projects in operation across Europe, notably the use of minewater in the fifth-generation district heating and cooling scheme at Heerlen in the Netherlands (Buffa *et al.*, 2019), see Walls *et al.* (2021) for a comprehensive review. These systems have the potential to service several larger buildings or district heating networks (Verhoeven *et al.,* 2014; Boesten *et al.,* 2019) and therefore are more likely to be implemented by development companies as part of a heating network at a neighbourhood scale rather than individual buildings. At the time of writing, in the UK, there are five operational minewater heating schemes; three in Gateshead in the north-east of England (Banks *et al.,* 2022, The Coal Authority, 2023a; IEA, 2023b), a small pilot scheme at the Coal Authority Dawdon office in County Durham (Bailey *et al.,* 2013) with a large scale scheme under development at the same site (The Coal Authority, 2023b) and a single shaft scheme in operation at Markham colliery in Derbyshire (Al-Habaibeh *et al.*, 2018). Five minewater schemes are currently non-operational or have been decommissioned (Walls *et al.,* 2021). In March 2023, the British Geological Survey (BGS) opened the Glasgow Observatory, a NERC field research facility designed to investigate the use of minewater as a source of heat (Monaghan *et al.*, 2022b, UKGEOS, 2023). Heat can also be extracted from minewater treatment works or passive drainage on the surface. Often, flooded mines are required to be continually pumped to stop the water levels from rising and flooding the surface or contaminating aquifers. As a result, large quantities of minewater are already being pumped to the surface, treated, and discharged, wasting the potential heat that could be extracted from the water. Using pumped water from treatment schemes as a heat source is often described as a 'low hanging fruit' for minewater geothermal heat (Bailey *et al.*, 2013, Bailey *et al.*, 2016; Walls *et al.*, 2022).

The temperature of UK mine waters range between 9.5°C at 100 metres below ground level (m bgl) to 40°C at 1200 m bgl (Farr *et al.,* 2020). Unlike surface temperatures, which are highly variable throughout the year, subsurface temperatures remain stable, and as a result minewater geothermal systems have a greater thermodynamic efficiency than air-sourced or surface water-sourced systems (Bailey *et al.,* 2016). Mine waters are generally warmer than surface temperatures in winter (Bailey *et al.,* 2016), and cooler than the surface temperatures during summer and so can be used to provide heating and cooling accordingly (Verhoeven *et al.,* 2014; Banks, 2017).

Abandoned mines are increasingly being investigated as underground thermal storage for the inter-seasonal storage of heat in district heating networks, known as Mine Thermal Energy Storage (MTES) (Bracke and Bussmann, 2015; Hahn *et al.,* 2018a). In this case, mine workings act as a large hot water storage tank, where heat generated in the summer, generally from solar thermal, can be retained until it is needed in the winter. This is a relatively new concept and there are a handful of MTES schemes in feasibility or early-stage development in the Ruhr area of Germany (Hahn *et al.,* 2019; Kallesøe *et al.,* 2019; Koornneef *et al.,* 2019) and thermal storage has been incorporated into the existing Mijnwater project in Heerlen, Netherlands (Verhoeven *et al.,* 2014; Walls *et al.,* 2021). In this paper we include thermal storage technologies that store heat from sources on the surface such as solar thermal or waste industrial heat within the term 'minewater thermal' (MWT) resources.

3.1.2 Minewater thermal development in the UK

Minewater thermal technologies are relatively underutilised in the UK, despite the extensive mining legacy infrastructure left behind by the long history of mining. A potential minewater development must obtain permits from various regulators before it can proceed. The Coal Authority provides 'minewater heat access agreements' for minewater thermal projects in abandoned coal mines (GOV.UK, 2023). Additionally, to extract water from a mine, a groundwater abstraction licence is required and to return the water to the mine a 'permit to discharge' is required from the relevant environmental regulator (GOV.UK, 2023a).

Many studies have investigated public and stakeholder perceptions of new sub-surface energy technologies (e.g. Ryder *et al.* 2023; Westlake *et al.*, 2023), but there is very little research on public awareness or perception of minewater thermal, or on societal engagement on technology development, implementation, and operation (Roberts *et al.*, 2023). A series of workshops with public participants held in 2019 found that while awareness of minewater thermal technology is low, participants were largely supportive of the technology once they learnt what it is (Dickie *et al.*, 2020). Perceived benefits particularly relate to the positive reuse of legacy mining infrastructure, but people raised concerns about risks of subsidence and sinkholes, as well as cost and responsibility - particularly around who would be liable if something goes wrong with the system. There is no previous research on the awareness of minewater thermal in the construction and engineering industries or local authorities in the UK.

In Scotland, low-carbon heating solutions are being incentivised by the Scottish Government by legislating a ban on the use of "direct emission heating systems" (i.e. those which are fuelled by gas, oil, or biomass) for space heating and hot water for individual buildings built after 1st April 2024 (Scottish Government, 2022c; Building (Scotland) Amendment Regulations 2023). This is part of the measures to meet the net-zero greenhouse gas emissions target of 2045 (Climate Change (Emissions Reduction Targets) (Scotland) Act 2019). This ban means that housing developers will have adjust their practices in order to build new buildings that are heated using low carbon heat sources or by implementing standards such as the passivehaus standard to significantly reduce the heat demand of the buildings (Energy Savings Trust, 2022).

Successful long-term development of minewater thermal resources requires a range of stakeholders to know about the technology, and for skills and supply chains to be in place to implement such schemes effectively. If awareness of minewater thermal technology remains low, its use will not be considered among the range of available low-carbon heating solutions by development companies or their clients, leading to missed opportunities. For minewater thermal to be considered at an early stage of the project life cycle, relevant stakeholders must be aware of its potential to provide heating for their development. Otherwise, adapting a design to include minewater resources as a heating source or thermal storage solution will cost time and money, especially once planning permission has been granted.

Here we investigate, for the first time, the awareness and perceptions of minewater thermal resources amongst key stakeholders that would be involved in the future development of minewater resource projects. We examine perspectives from decision-influencers and decision-makers across a project's lifecycle. As well as understanding perceived barriers and opportunities, we aim to establish what type of information or support stakeholders would require to consider minewater as a low carbon heating solution at the earliest stages of their projects. From these insights, we can determine what action is required or should be prioritised - and by whom – including the role of geoscientists, to accelerate technology uptake.

3.2 Methods

Twelve semi-structured interviews were conducted between January and April 2023. To inform our research scope, and to identify and recruit interviewees, we first mapped potential stakeholders who could play a part in the development of a minewater thermal scheme at the different stages of project development (Figure 3.1). Stakeholders were typically either (a) 'clients' of low-carbon heating, such as housebuilding companies or local authorities, and (b) organisations that provide information to heat 'clients' such as engineering consultancies, academia and the third sector. As minewater resource projects are typically high CAPEX multi-user systems, we specifically excluded building residents or users; while community driven projects are a possibility, any such projects would have to engage with stakeholder groups in Figure 3.1 to take forward such an initiative. In total, seven key stakeholder groups were identified including: Property developers, Landowners, Consultancies, Supply Chain companies, Utility companies, Academia & Third Sector, and local authorities. Each stakeholder group and their role in minewater resource projects are detailed in Table 3.1. Through a combination of convenience (utilising professional networks on heat decarbonisation) and snowball sampling we aimed to recruit at least one interviewee from each stakeholder group. Importantly, we aimed to interview people who are 'experts' in their industry or field, rather than experts in minewater thermal resources and technologies, and we made this very clear when approaching potential participants.

Interviews were semi-structured, with questions that explored the interviewee's knowledge, awareness and experience of minewater thermal, perceived advantages and disadvantages, routes for growing knowledge and confidence, as well as their wider knowledge of heat decarbonisation and their current role. We did not ask the interviewees any questions about the role of geoscientists in the interviews. In total, 25 stakeholders were approached for interview, leading to twelve interviews being conducted between January and April 2023 (48% sample success), see Table 3.2 for details. During the project timeframe it was not possible to recruit a participant from a local authority and so this stakeholder perspective is not represented in our sample. One participant occupied two stakeholder categories (see Table 3.2). All interviews were recorded and transcribed verbatim, and the transcripts were emailed to the interviewees, giving them opportunity to redact anything that they did not want in the public domain or to be included in the analysis. The interviews were then anonymised and allocated an ID reflecting the stakeholder group to which they belong (Table 3.2). Data were analysed using an inductive and iterative process of thematic analysis, which involves “developing, analysing and interpreting patterns across a qualitative dataset” (Braun and Clarke, 2021) and broadly follows a seven-step process: transcription, familiarisation, coding, searching for themes, reviewing themes, defining themes, and finalising analysis (Braun and Clarke, 2013). We used NVivo software to code the transcripts into themes producing a longlist of 76 codes that were grouped into four topics (perceived advantages, perceived disadvantages, information required, and wider issue) to be analysed in more detail.

	Type of stakeholder	Example stakeholder
1. Project inception	Heat 'clients' including • Those requiring heat • Those requiring thermal storage	• Property developers and housebuilders • Landowners • Local Authorities • District heating operators • Waste heat producers • Public sector buildings • Anchor load buildings • Community organisations
2. Feasibility	• Regulators to provide advice, licenses or permits. • Companies to investigate the minewater resource and the potential heat or storage capacity • Companies to investigate the suitability of the site for development	• Environmental regulators and The Coal Authority • Consultancies and contractors for site investigation • Academia and research organisations, and third sector organisations
3. Design	• Companies to design the heating system or heat network • Companies to design the buildings which will receive the heat	• Architects • Engineering consultancies • Supply chain companies • Academia & Third sector • Community organisations
4. Construction	• Companies to build the infrastructure • Companies to manufacture and build the heating system • Companies with existing subsurface infrastructure assets	• Construction companies • Engineering consultancies • Supply chain companies • Utility companies • Building regulators and inspectors
5. Operation and maintenance	• Companies to maintain the system • Domestic and commercial end users of the heat	• Engineering consultancies • Supply chain companies • Utility companies
6. Decommissioning	• Companies to demolish or repurpose the system • Companies to design and build an alternative system	• Engineering consultancies • Construction companies • Supply chain companies • Utility companies • Regulators • Local Authorities • Community organisations

Planning authorities to provide planning permission — Local Authorities

Figure 3.1: Potential stakeholders who could be involved in delivery, regulation, or end-use of a minewater thermal project, defined by the stages of a project life cycle. Note: This list is not exhaustive and will vary with project type and context.

Table 3.1: The stakeholder groups identified during the stakeholder mapping exercise and the rationale for their inclusion, along with the type of companies that were interviewed during the study.		
Stakeholder group	**Role, or 'stake'.**	**Company types interviewed**
Property developers (D)	Property developers need to make informed decisions about what kind of low-carbon heating systems they are going to include in their developments. If they are unaware of minewater thermal as a viable option for their site then it won't be considered, even if the site is underlain by mine workings.	• Housebuilding company • Registered social landlord • Urban regeneration company • Land and property development company
Landowners (L)	Landowners may be aware of mines on their land that they could utilise for heating for existing buildings or as a development opportunity.	• Land development company • University
Consultancies (C)	Consultancy companies can be involved at several stages of the project lifecycle and provide information and designs to other stakeholder groups such as property developers and landowners They need to be aware of the different options for low-carbon heating and the various benefits and drawbacks.	• Engineering consultancy x2 • Sustainability company
Supply Chain companies (SC)	Supply chain companies would need to understand whether their products and services would interact differently with a minewater heat source compared to any other kind of heat source.	• Heat pump manufacturing company
Utility companies (U)	These companies have existing sub-surface assets such as water and gas pipes and telecommunication cables so they would want to know if a minewater district heating scheme was going to be installed and how it might affect their assets.	• Energy company
Academia and Third Sector (AT)	Academics: assessing or evaluating the resources, developing new technologies, research, education. Third sector stakeholders could play a number of roles including as end-users of heat, enablers of net zero transitions, facilitators of change, or community organisations.	• University • Community land organisation
Local authorities	Local authorities may have mine workings on their land that could be utilised to heat local authority owned buildings or social housing, helping them move towards decarbonisation targets. Planning authorities need to be aware of the potential effects of a minewater scheme to make informed decisions about developments.	n/a

Table 3.2 The job roles of each of the expert stakeholders interviewed during this study and an ID code which will be used throughout the results section to refer to the participants.			
ID	**Interviewee role**	**ID**	**Interviewee role**
D1	Project Manager	C1	Energy Engineer
D2	Technical Director	C2	Entrepreneur/ Consultant
D3	Head of Regeneration	C3	Principal Engineer
D4	Development Director	L1	Sustainability Executive
SC1	Director	AT1	Manager
U1	Head of Business Development	AT2	Lecturer

3.3 Results

The range of stakeholders involved across the lifecycle of a minewater thermal (MWT) resource project are shown in Figure 3.1; the list is not exhaustive and will vary with project type and context. What is clear however is that the seven stakeholder groups that we identify – eight including heat users or consumers and wider public stakeholders – are all critical to project delivery. The twelve interviewees gave a wide range of answers that were inconsistent within and across the stakeholder groups, highlighting both the complexity of decarbonising heat and the current uncertainty around development of minewater thermal resources in Scotland. Nevertheless, participants from different stakeholder groups often shared the same concerns, and common topics were discussed by several participants. We acknowledge that this is a small sample, however we were aiming to collect depth rather than breadth of data.

We present the results in four parts: first we look at the level of awareness of the interviewees, before moving on to examine key themes raised by interviewees that are specific to minewater thermal, followed by themes that are about heat decarbonisation more broadly, and finally we explore the information interviewees felt that stakeholders would support minewater developments. Note that in the results section, we are simply reporting the perceptions of the interviewees and are not seeking to challenge their assumptions.

3.3.1 Levels of awareness and perceptions of minewater thermal technology

Ten out of the twelve participants were aware of minewater thermal as a low-carbon heating technology prior to being interviewed, but the depth of knowledge varied; two participants had only heard of minewater thermal in passing, three participants had some basic knowledge of the technology, and five participants had a detailed knowledge of how the technology worked and gave examples of projects. When recruiting participants, we stressed that no prior knowledge of minewater thermal was required to participate in our study. However, participation bias is still highly likely in our sample, not only will those who know the technology, or have vested interest, be more likely to be motivated to respond to an invitation, but also we utilised heat decarbonisation professional networks to identify potential interviewees. Therefore, we expect that the level of minewater thermal technology awareness amongst wider stakeholders could be much lower than that reflected in our sample. All interviewees were knowledgeable about different methods of decarbonising heat, including heat pumps, district heating schemes, retrofitting or direct electric heating. There was no consistency across interviewees on how they learned about minewater, i.e. the sources of information that they used were different. For example, each of the four Property Developer stakeholders cited a different source of information (Figure 3.2).

Despite not securing participation from a local authority representative, there is evidence from our interviewees that awareness of minewater thermal among this stakeholder group is low. One participant had worked with local authorities across Scotland on policy for decarbonising heat, but the participant had never heard of minewater thermal or heard it discussed in their work: "*local authorities across Scotland, all 32 of them…nobody talked about minewater geothermal"* (AT2).

Among the interviewees, knowledge about minewater thermal resources was concentrated among professionals who work in adjacent industries or who already have an awareness of the subsurface from their job or education. Outside those circles few found a lack of detailed understanding of the use of minewater thermal technologies.

Figure 3.2: The routes through which participants first became aware of minewater thermal as a technology. Each section on the outside wheel represents one of the twelve participants.

3.3.2 Interviewee perceptions: benefits or enablers of minewater thermal

All interviewees were generally positive about minewater thermal technologies; each mentioned at least one benefit of the technologies. Six themes regarding benefits or enablers were generated from interview data, shown in Table 3.3 and each theme was evident across multiple stakeholder groups. *"I'm pretty positive about [minewater thermal], albeit it hasn't yet really properly sort of hit the headlines for the scale of opportunities that I see"* (U1).

Table 3.3: Six categories of benefits of minewater thermal as perceived by interviewees, organised by stakeholder group and specifying interviewee ID. (DHN = district heat network).

Stakeholder group	Perceived benefits of minewater thermal technologies					
	Potential for thermal storage for a DHN	Existing skills for MWT	Co-location with demand	Social or community benefits	Using legacy infrastructure	Low surface impact
Property developers (D)	D1, D3		D1		D2	D4
Landowners (L)		L1				L1
Consultancies (C)		C3	C3	C2	C1	
Supply chain (SC)		SC1	SC1			
Utility (U)	U1	U1				
Academia and Third Sector (AT)	AT2			AT1, AT2		
Total (count)	**3**	**4**	**3**	**3**	**2**	**2**

3.3.2.1 Use as inter-seasonal storage for district heating networks

The use of abandoned mine workings for thermal storage was one of the most discussed benefits, perceived by four participants across three stakeholder groups (D1, D3, U1, AT2; Table 3.3). Of those participants, three had personal experience of working with district heating networks or similar projects. As a Utility stakeholder who had experience of developing and operating district heating networks expressed: *"it's potential to store [thermal energy] … potentially is a massive advantage. There aren't many ways of being able to store large volumes of water without putting it somehow underground.* (U1).

3.3.2.2 Existing skills and labour needed for minewater thermal projects

Four interviewees from four stakeholder groups (L1, C3, SC1, U1) stated that many of the skills required to successfully construct minewater thermal projects already exist within the workforce in Scotland, such as drilling boreholes and laying underground infrastructure. In addition, the specialist knowledge and experience of the subsurface that will be required for MWT was also perceived to be abundant in Scotland.

The ability and knowledge to manufacture and install heat pumps and heating systems was mentioned as something that already exists within the economy (SC1). The manufacture of large heat pumps is similar to manufacturing refrigeration units, hundreds of which are produced every year for supermarkets, so there is already a well-established supply chain for this manufacturing activity and the wider supply chain should be able to accommodate the additional demand for more industrial heat pumps in the future. The same participant also felt that there was an abundance of skills and trades in the wider economy that could be used in the heat pump manufacturing industry: *"The manufacturing [of heat pumps] is fairly basic welding and pipe fitting skills and wiring, and these are trades that have hundreds of thousands of people active in the UK"* (SC1). However, all these existing skills need to be organised and coordinated to develop a future minewater thermal industry: "A*ll of the elements exist; they just need to be kind of collected in the right way"* (C3).

3.3.2.3 The proximity of mine workings to heat demand

The co-location or overlap of heat demand with the location of the mine workings was raised as a benefit of minewater thermal by interviewees across three stakeholder groups (D1, C3, SC1): "*A key benefit of minewater is that the mines are geographically located where the demand is*" (C3). Co-location was seen as an opportunity to provide locally sourced heat for local heat demand because, as in many ex-mining locations, the Central Belt of Scotland has a large concentration of former mining areas which remain as population centres.

3.3.2.4 Potential for community benefits

Three interviewees from two stakeholder groups (C2, AT1, AT2) discussed the potential for community benefits that minewater thermal schemes could provide. They speculated whether minewater could provide co-benefits to a community alongside heat decarbonisation; *"this could be a potential solution that addresses some of the socio-economic factors alongside heat decarbonisation"* (AT2). One participant suggested that locally generated electricity, such as from a local wind farm, could be sold to a minewater scheme at a discounted price to power the heat pumps, and that residents local to a minewater scheme could benefit by receiving a discount on their heating bills. This could help to address fuel poverty, which disproportionately affects coalfield areas more than other regions of the country (Foden *et al.*, 2014). Different ownership models of MWT resources were also discussed, with one participant suggesting that residents could have ownership over a minewater scheme that would provide heat to their area: *“That sense of ownership over something, that's such an important part of some of these communities.”* (AT2)

3.3.2.5 Other perceived benefits of minewater thermal technologies

Two stakeholders (D2, C1) highlighted the positive reuse of legacy infrastructure as a benefit of minewater thermal, one which could change the perception of having mine infrastructure on a site. *“I think it’s something that is certainly of interest to a lot of stakeholders in Scotland… opportunity of decarbonising heat [and] making use of essentially what is an existing asset is very much something that people would be interested in.”* (C1). Low surface impact was mentioned as a benefit by two stakeholders (D4, L1) as they felt that once a minewater thermal scheme had been completed, any infrastructure on the surface could be quite compact and unobtrusive.

3.3.3 Interviewee perceptions: disadvantages or barriers of minewater thermal

Potential drawbacks and barriers to MWT identified by interviewees are summarised in Table 3.4. Unlike the perceived benefits, the barriers raised are more often specific to particular stakeholder groups, and four were raised by only one participant, though the three key disadvantages raised span across at least two stakeholder groups.

Table 3.4: Seven categories of disadvantages of minewater thermal as perceived by interviewees, organised by stakeholder group and specifying interviewee ID.

Stakeholder group	**Perceived disadvantages of minewater thermal technologies (MWT)**						
	Cost or finances	Feasibility risks	Regulation of MWT	Low heat capacity	Lack of heat demand	Other approaches more viable	Lack of job creation
Property developers (D)	D1, D4		D1				
Landowners (L)							
Consultancies (C)	C3	C1, C3					C2
Supply chain (SC)				SC1		SC1	
Utility (U)	U1	U1	U1		U1		
Academia and Third Sector (AT)							
Total (count)	**4**	**3**	**2**	**1**	**1**	**1**	**1**

3.3.3.1 Cost of minewater thermal projects

Cost, the most discussed challenge, was raised by four participants across three stakeholder groups (D1, D4, C3, U1; Table 3). They felt that constructing a minewater thermal scheme was more expensive relative to other low-carbon heating solutions, such as water-source or air-source heat pumps. This higher cost was attributed to high upfront capital cost for feasibility studies, drilling exploratory boreholes and construction, but also to the operational cost of electricity to operate the heat pumps. The large capital investment required for a minewater thermal scheme was seen to incur a lot of financial risk. C3 felt that the problem with financing minewater thermal schemes was not the amount of money that was required but the way the finances are structured and suggested that new business models would unlock the potential of these projects.

Conversely, it might not be as expensive to drill into shallower mines compared to other deeper geothermal resources, as one participant stated: *"Minewater is attractive because it's fairly shallow and therefore fairly cheap"* (SC1). Another participant said that information revealed through the UKGEOS Glasgow Observatory project (UKGEOS, 2023) was de-risking the process and demonstrating that the cost might not be as high as previously thought: *"The ability to access the mine workings … maybe not that cost prohibitive, as it may first appear, and the ability to sink a few boreholes to access them maybe at different locations… looks much less of a risk than perhaps it has been historically, I think."* (D1). For D4, a feasibility study carried out for their site found that it was cheaper to use minewater from an adjacent minewater treatment works as a heat source compared to installing ground source heat pumps with a borehole array: *"The costs … for ground source heat pumps were mind-boggling, the costs for the minewater less so, but would still be a significant investment over a period of time."* (D4)

3.3.3.2 Pre-construction/ feasibility risks and technical complexity

Feasibility risks and technical complexity were mentioned as a disadvantage by three participants (C1, C3, U1). These participants felt that constructing a minewater thermal scheme presented a larger risk than other low carbon heating solutions such as water-source heat pumps, and the issues link to financial risk and project cost. The most commonly mentioned type of risk was pre-construction risks, such as the cost of locating and accessing the mine workings, predicting the size of the thermal resource, drilling risks, the potential of missing the mine workings, or that insufficient amounts of water to produce heat being abstracted during testing to make a scheme economical : *"You could have a fantastic resource that's been very well surveyed but if you can't drill and hit the [coal] seam then you've got nothing. Well less than nothing, you've spent all this money doing the drilling and you've got nothing from it."* (C1). There were also concerns about the technical feasibility of minewater schemes and the ability to scale it up. One participant felt that the complexity of minewater thermal schemes would be a major barrier to their successful development. "*I think the biggest barrier for minewater is the … technical complexity up front and the risk of aborted drilling and not getting the resource that you forecast."* (C3). However, U1 felt that feasibility and technical risks can be overcome by having good data for the subsurface and predictive modelling. *"I think the prediction of the resource and …uncertainty, and therefore commercial risk, in accessing the resource that is something that we've got time to resolve. If it's not resolved, it's a barrier."* (U1).

3.3.3.3 Regulation of minewater thermal resources

Regulation and governance of minewater thermal resources was discussed by two participants from two groups (D1, U1), both in terms of the current complexity in UK regulation to be able to access mine workings and construct a minewater thermal resources, and in relation to the ownership, licencing, or purchasing of the heat produced from future minewater thermal schemes. At the time of writing, geothermal heat is not legally recognised as a natural resource in the UK, and there is no specific regulatory regime for shallow geothermal energy, which can present difficulties when it comes to issues of ownership and regulation for geothermal resources (Abesser *et al.*, 2018; McClean and Pedersen, 2023).

Another layer of regulation to be carefully considered with minewater thermal resources, is that of storage. If the mines are used as an underground thermal store by one organisation, how will regulations address other users who might tap into the same mine workings and take out heat that is stored in the mine. One participant speculated that it would be "*slightly disastrous if I decide to build a store in the mine workings and then [another development] up the road gets another license [and] gets the benefit of the store I've created, because [of] a hydraulic gradient where all the water flows to them and they get all the heat out. So there's a need for…carefully thinking about how to license the subsurface"* (U1). To be able to develop projects at the speed needed to decarbonise heat, the current regulations and permitting process for minewater thermal resources will need to be streamlined, or specific minewater regulations written.

3.3.3.4 Other perceived disadvantages of minewater thermal technologies

Other disadvantages identified included lack of local large-scale heat demand, low heat capacity, lack of job creation, and the concern that other solutions are more viable. U1 stated that the most significant barrier to the development of minewater thermal projects in Scotland is the lack of demand for low-carbon heat. Without nearby heat demand and the heat supply infrastructure to connect buildings to the source, any low carbon heat source is rendered useless. SC1 felt that minewater thermal would not provide sufficient heat capacity for city-scale district heating networks, which they felt presented a lot of risk for prospective investors in these schemes. They argued that minewater should not be considered above heat sources that present less risk and cost, such as surface water sources: *"in the centre of Glasgow, [using] coal mine [thermal] resource would be a complete mistake because the river could probably sustain about 750 MW of heat extraction"* (SC1). C2 expressed concern about the lack of jobs that minewater thermal schemes would create for local communities. Post-construction, the system would be relatively simple to maintain and would potentially only create one or two maintenance jobs, which would probably be filled by the operator, not by people from the local area.

3.3.4 Wider systemic issues for heat decarbonisation

Several broad economic, political, and social issues were raised across all stakeholder groups, which go beyond the development of a minewater thermal industry in Scotland and apply to the heat decarbonisation more generally. The five most prominent themes are summarised in Table 3.5.

Table 3.5: A summary of the wider issues raised throughout the interviews in relation to the decarbonisation of heat in general.

Stakeholder group	Wider issues raised				
	Skills gaps and labour shortages	Need for demand for low-carbon heat	Cost of electricity	Cost of living crisis and fuel poverty	Cost of decarbonisation of heat
Property developers	D2	D1	D3	D3, D4	D3
Landowners	L1	L1	L1		
Consultancies	C2, C3		C3		
Supply chain		SC1	SC1		
Utility		U1		U1	U1
Academia and Third Sector	AT2	AT2		AT1, AT2	AT2
Total (count)	**5**	**5**	**4**	**4**	**3**

3.3.4.1 Skills and labour for the decarbonisation of heat

Despite interviewees expressing confidence in skills and supply chain for minewater thermal in Scotland, concerns relating to skills and labour for heat decarbonisation more generally, such as growing shortage of skills, labour, and products for heat decarbonisation were mentioned by five interviewees across four stakeholder groups (D2, L1, C2, C3, AT2). Two interviewees (D2, AT2) felt that that there are currently not enough installers available to meet decarbonisation needs, and that too few people are being trained. As AT2 expressed, further education courses *“can't take very many students, and I don't know that they have that many students applying either… [not] in the kinds of volume that we need. So there's a real capacity issue.”* This issue cascades to heat pump maintenance: two participants, who both own heat pumps that have needed maintenance or repair, have struggled to find anyone to come and fix them. The companies they contacted told them to replace the heat pump or that they only carried out installation. *“Everyone we were ringing was saying, we do installs”* (AT2). This shortage will impact the quality of heat pump installation: “*If in the next year everybody went, ‘I need a new heating system’ …you'd get some really poor installations.*” (AT2).

Consultant C3 felt that better communication between consultants and contractors will be needed to streamline heat pump installation: *“You have this kind of split between the consultants, who look at all of the options, but they themselves haven't ever installed one of those projects. They kind of rely on the supply chain to feed them information about how those different technologies work.”* (C3).

3.3.4.2 Low carbon heating demand

Demand for low carbon heat remains low by comparison to high carbon options, which is a major issue raised across five different stakeholder groups (see Table 3.5). For schemes such as district heating networks or minewater thermal schemes to go ahead, developers need to be confident that there will be enough demand from customers and anchor loads[8] to connect to the network to make the investment case: *“Developers will require that there's a strong demand; they're not going to develop networks without the data that say, here's the demand, here's the supply”* (L1).

3.3.4.3 Electricity markets/ cost of electricity

The high retail cost of electricity and electricity pricing in the UK is considered a major barrier to uptake of low-carbon heating including minewater thermal projects, raised by four interviewees from three stakeholder groups (D3, L1, C3, SC1) and considered by two participants to be the single biggest barrier for projects. SC1 said that the largest operational cost of projects using ambient sources of heat boosted by heat pumps is the cost of electricity that is purchased to operate the heat pumps. In addition, the price of electricity is subject to a volatile market and the

[8] An anchor load is a building which has a large heat demand, such as a hospital, which are often the first to be connected to a district heating network. The Scottish Government has defined an anchor load as a publicly owned building which has a heat demand over 100 MWh per year (Scottish Government, 2019).

uncertainty created by this fluctuation could make developers hesitant to invest in low carbon heating technology. *"If you're asking developers what they want, they want certainty, and one of the aspects that undermines certainty is what's the price of the electricity for this development going to be"* (SC1).

3.3.4.4 Cost of living crisis and fuel poverty

The cost-of-living crisis and fuel poverty were mentioned by four interviewees across three stakeholder groups (AT1, AT2, U1, D3). When the interviews for this study were being carried out (Jan – Feb 2023), the cost-of-living crisis was a major headlining issue in the UK media. In December 2022 it was reported that 23% of adults in the UK were unable to keep comfortably warm in their living rooms (Lawson, 2022) and that paramedics in Scotland were seeing an increase in people becoming unwell due to living in a cold home (Picken, 2023). It is likely that the contemporary cost-of-living crisis may have affected the responses to the interviews, mainly in relation to the cost of heating for communities and consumers. There were concerns from two interviewees (D3, D4) that decarbonising heating could lead to increased costs for customers and an increase in fuel poverty in the short-term, due to the high cost of electricity compared to gas. *"Until we provide that energy [at] an equitable rate, we're actually exacerbating fuel poverty whilst decarbonising. So that's a horrible crossover that exists and hopefully [one] we're able to tackle."* (D3). Another interviewee (AT1) said that the cost-of-living crisis means that decarbonising heat is not a priority for people, as they are *"very focused on the immediate challenges in front of them"* (AT1). However, AT1 also felt this was shifting a little bit as the crisis is putting renewed focus on energy efficiency challenges, including heating.

3.3.4.5 Cost of decarbonisation of heat and who will pay?

A theme common across three stakeholder groups, was who should take responsibility for the large financial cost of the decarbonisation of heat. Decarbonising heat in the UK is estimated to cost between £120 and £450 billion (Cowell and Webb, 2021). The cost of continued use of natural gas heating is also considerable and brings other negative consequences for environmental and public health and the climate.

Interviewees expressed different opinions about who should pay and when, but there was consensus that heat decarbonisation needs to be viewed over the long-term, that it could not be entirely funded by the public purse, but also that the cost could not be entirely shifted onto consumers. New business models for low carbon heat that can accommodate these challenges are clearly needed. It was also suggested that low carbon heating projects should be seen as a long-term investment to tackle fuel poverty as well as heat decarbonisation. *"You need to be* *thinking longer term than the amount of time people generally live in their homes, the amount of time a political party's in power, the ability to realise the value of doing it needs to see much longer time scales and there needs to be a mechanism for financing that"* (U1).

3.3.5 What information would build confidence in minewater thermal?

When asked what information would build stakeholder confidence in considering minewater thermal for their projects, six themes were deduced and are summarised in Table 3.6. Themes were common across interviewees, rather than specific to particular stakeholder groups or individuals.

Table 3.6: A summary of the information that developers or investors need or want to know about minewater that would encourage them to consider it among other low carbon heating options.

Stakeholder group	**Key information required**					
	Trust or confidence in the technology	Mapping the heat supply and demand	Cost or financial risks	Sustainable supply of heat	Impact on communities	Carbon savings
Property developers (D)	D2, D4		D4			D1
Landowners (L)		L1	L1	L1		
Consultancies (C)	C1, C2	C2				
Supply chain (SC)				SC1		
Utility (U)	U1				U1	
Academia and Third Sector (AT)		AT1, AT2	AT2		AT1	
Total (count)	**5**	**4**	**3**	**2**	**2**	**1**

3.3.5.1 Information to build trust or confidence in the technology

Three interviewees (D4, C1, U1) felt that sharing examples of existing minewater thermal schemes and the outcomes would help 'heat clients' to trust the technology. As C1 reflected, it can be difficult to make sure "*stakeholders are familiar with the technology and are able to come to the table and really try to take everything on board…I think from a de-risking perspective if you have that proof and evidence, it makes things a lot easier to work with"* (C1).

Three participants (U1, C2, D2) mentioned that many people associated onshore borehole drilling with hydrocarbon extraction *"and I always say it's a very different thing"* (C2). U1 felt that negative public attitudes could be a major barrier to the development of minewater thermal projects. They said "*there isn't enough engagement with communities, there isn't enough listening to them… and being upfront and early about it." (U1).* They also suggested early projects could *"demonstrate that negative consequences won't happen or if negative consequences do happen, we got the mitigation plan in place, to say this is what we do to stop it [the negative impact]."* (U1).

This participant also said that heat consumers would also need to have confidence that this heat source was going to provide a reliable and resilient source of heat for their home or business. *"The customer needs to have confidence that what comes out of their pipe, and when I say customer, I also mean the housebuilder themselves, but they need to be convinced that what comes out of the pipe at their end is hot water."* (U1).

3.3.5.2 Mapping heat supply and demand

Four interviewees from three stakeholder groups (C2, L1, AT1, AT2; Table 3.6) highlighted the importance of having a good knowledge of the geology and geography of a site to define the potential for minewater thermal resources. Minewater thermal resources are spatially constrained and location-specific and therefore local heat demand is critical. One participant suggested that if all the spatial data was *"plugged into a GIS platform that all local authorities have, [then] they can work out the best siting of a proposed drill site [for minewater thermal]"* (L1).

Information on how many buildings could be heated using a particular minewater resource would also be crucial for technology uptake. One participant felt that this was particularly relevant for local authorities. *"If a council understands… you could heat all of your libraries and schools using this local minewater facility and it would cost you… X million up front…that's when they would start to be interested"* (AT2).

3.3.5.3 Cost or financial risks

Three participants (D4, L1, AT2) felt that further information and clarity around development and operational costs was key for stakeholders to consider minewater thermal in their projects. Assurance would be needed that using minewater thermal for a project *"doesn't wreck the financial appraisal, frankly"* (D4). One participant felt that cost was particularly important for local authorities because they are *"so constrained financially"* (AT2), and that local authorities would be interested in solutions that can help them achieve multiple goals at once, for example *"delivering decarbonisation, perhaps improving energy security, access to heat within the local authority owned properties and social housing"* (AT2).

3.3.5.4 Other key information

Two participants thought it was key to know how much water is in the mine, how much heat could be extracted from it, and how quickly heat will be replenished. *"With minewater, anybody making a development will want to know what the sustainable thermal extraction capacity is of a resource, what the cost of developing it is, and what the risk of not finding that resource is."* (SC1). Two participants raised the need to determine the impact of a scheme on local communities such as noise, contamination of water, or visual impact, and that community involvement would be key throughout the project lifecycle. *"Community engagement is a key part of minewater [development], because of the history of the communities around the mine"* (AT1). The potential carbon reduction that minewater thermal technologies could offer a development was raised by only one participant as something important for developers to know, given the upcoming ban on gas boilers in new buildings in April 2024.

3.4 Discussion

Interviews with six groups of stakeholders gathered different perspectives on minewater thermal resources and wider systemic issues surrounding heat decarbonisation. One of the key themes to come from the analysis is that of complexity. All participants had a range of views and each one suggested different solutions to the various problems raised. This reflects the inherently complex landscape of heat decarbonisation (Stewart *et al.*, 2020; Cowell and Webb, 2021). Heat decarbonisation is often described as a 'wicked problem' because it is a problem that has many solutions, and that the various solutions are *"embedded in the different world views and values of interested parties"* and therefore the solutions often conflict with each other (Cowell & Webb, 2021). In the short term, low-carbon heating solutions such as heat networks will be more disruptive and costly than sticking with the incumbent heating technology of natural gas (Cowell and Webb, 2021). While this is a major issue for policy makers (Lowes and Woodman, 2020), the Scottish Government have said that a "business as usual approach [to heating] is no longer viable" given the commitments to reaching Net Zero by 2045 (Scottish Government, 2022c).

Interestingly, although a complex landscape, our interviews found commonality in the perceived advantages of minewater thermal across stakeholder groups, the main advantage being the potential for abandoned mines to act as thermal storage for district heating networks. In contrast, the disadvantages were more specific to particular stakeholders and the greatest challenge for minewater thermal was perceived to be the cost of developing and operating the projects. There were a range of factors which interviewees felt that other stakeholders would need to start considering minewater, the most common theme being trust or confidence in the technology.

The complexity of the minewater thermal landscape detailed by interviewees in this study can be grouped into three topic areas: resource, cost, and people (Figure 3.3). Geoscience and geoscientists can play a role in each of these topic areas, particularly in providing the information that interviewees felt would support minewater thermal uptake which were displayed in Table 3.6. For each topic area (resource, cost, and people) we explore the role of geoscientists in turn.

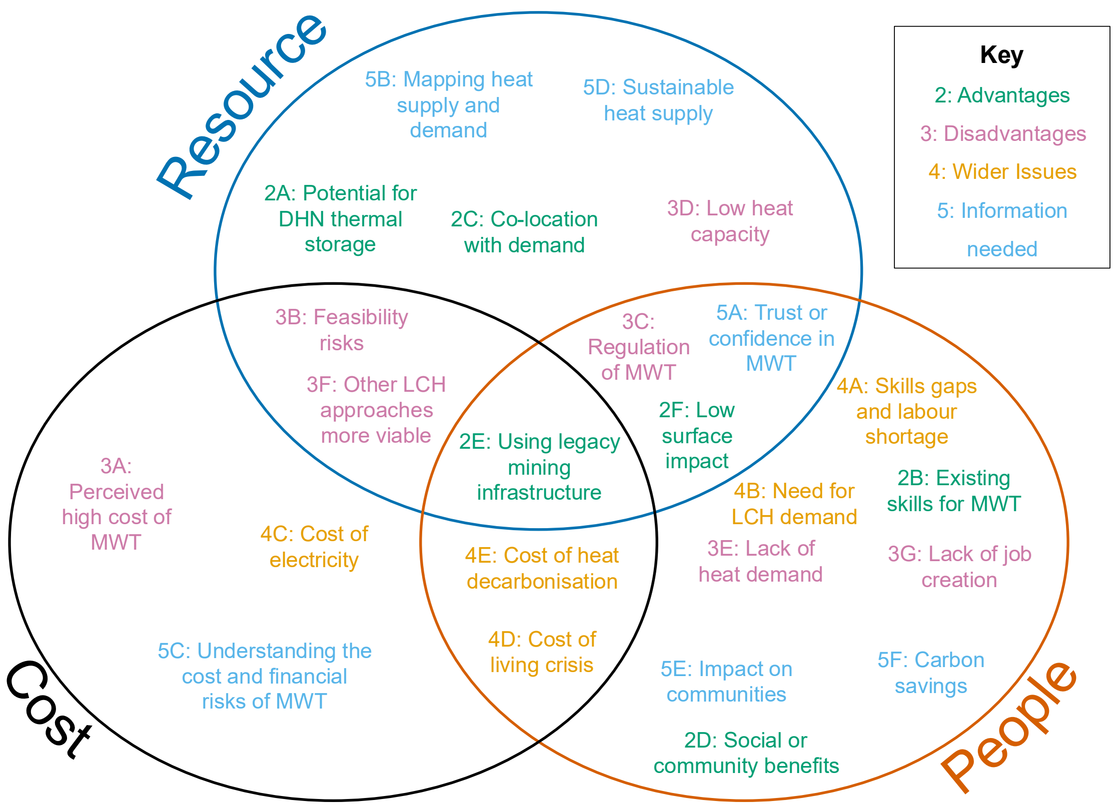

Figure 3.3: Venn diagram showing how the factors mentioned in the interviews (perceived advantage and disadvantages, wider issues, and information needed) fit into three topics: resource, people and cost. The number labels refer to the table that each factor is mentioned in, and the letters refer its position in the table, i.e. A is the first factor in the table. MWT = Minewater Thermal [Resources], DHN = District Heating Networks, LCH = Low Carbon Heat.

3.4.1 Resource: minewater thermal and heat demand

Firstly, a good awareness and understanding of the heat supply or storage capacity of the mine workings is fundamental for the development of these resources. Geoscientists have a clear role to play in quantifying the amount of heat that can be sustainably extracted from abandoned mine and over what timescales, as calculations require a detailed knowledge of the subsurface, the heat flow and water flow through the mine workings and the surrounding rock mass. One concern raised during the interviews was that minewater resources may not produce sufficient heat to make minewater projects viable; it is through geoscience knowledge and methods that sustainable resource capacity can be calculated.

Secondly, participants felt that having a good understanding of the location of heat demand and of minewater resources was important for development, and particularly assessments of whether and to what extent minewater resources could contribute to meeting local demand. This corroborates the findings of Stewart (2020) who also found that mapping heat supply and demand was key to the development of minewater resources.

Systematic maps of minewater thermal resources in Scotland were not publicly available when conducting our interviews in early 2023. However in May 2023, the Mine Water Geothermal Resource Atlas for Scotland was published, which identifies a total area of 370.3 km^2 across Scotland which has potential for using minewater as a source of heat (SpatialHub.Scot, 2023). At the time of writing, the Atlas does not link the subsurface minewater resources with surface factors such a heat demand or consider factors that influence suitability as an energy storage site.

Understanding heat demand is critical for a project to be commercial. Therefore, geoscientists must work alongside other disciplines like energy geographers, social scientists, and engineers to map out the co-location of minewater resources with surface level factors. This mapping could lead onto the creation of a hierarchy of heat sources that considers the geography of each location. As one participant suggested: *"If I've got an air source heat pump, energy from waste, industrial waste heat, I've got some mine workings, I've got a river, I've [got a] sewer. If you could rank all of those and say in this location, energy from waste has the lowest cost of heat. Maybe the industrial waste heat is next. But there's a hierarchy of those, and as the system grows, you go … I need this one now. And at some point minewater geothermal fits into that box, and once it's installed and connected, it contributes to the system."* (U1). This would be a place-specific process as each location would have different requirements and resources, or as one participant put it: *"[What] needs to happen in the house building industry is, to see local geographic anomalies as an opportunity rather than a problem."* (D2). This links to the concept of 'spatial interdependency' when infrastructure systems are in close proximity to each other and can have symbiotic or parasitic effects on one another (Gürsan *et al.,* 2023). Each area has its own geospatial characteristics and challenges, and if a district heating system can take advantage of all the different heat sources in its geographical area, then it can provide a more flexible and resilient system for the heat consumers, and perhaps unlock unexpected latent benefits (Gürsan *et al.,* 2023). Due to the highly variable nature of geography, every location will have a different set of heat options, different socio-economic context, and existing infrastructure system and each place will evolve in its own way. Thus, Gursan *et al.* (2023) state that every location will need "a unique master plan", which is very similar to the LHEES programme developed by Scottish local authorities during 2023 (Scottish Government, 2019). A hierarchy of low-carbon heat options would be complimentary to LHEES and could the optimal heat sources for a district heating network to be developed based on the geography of their site. Geoscientists need to be able to actively listen and communicate effectively and work collaboratively with other heat providers, district heating network operators and local authorities or other private developers. Considering minewater thermal as one heat source amongst others could reduce the risk of constructing a minewater scheme: other potential heat sources (e.g. waste industrial heat) could provide resilience to heat networks, and as such, an economy of scope rather than an economy of scale approach could help to reduce risk and costs (Panzar and Willig, 1981; Werner, 2017).

However, minewater thermal resources differ from many other heat sources due to the additional function that mine workings could play as thermal storage, which could be invaluable to the development of city scale district heating networks, and resilience to a renewable-heavy energy system. As an emerging concept, there remains much geoscientific work to investigate the potential of mine workings for energy storage, risks associated with thermal charging and discharging and how such technologies could be practically and safely implemented (Bracke and Bussmann, 2015; Hahn *et al.,* 2018; Jagert *et al.,* 2018; Shipton et al 2024).

3.4.2 People: minewater thermal and society

A crucial part of heat decarbonisation is the need to consider people and society as part of the system, because without that the system will not function. Decarbonising heat requires a range of stakeholders to change practices, from policy down to household level, and skills and supply chains to be in place together with knowledge exchange to ensure good practice.

Interviewees emphasised that trust and confidence in the technology were key to developers starting to investigate minewater as a solution, and for consumers to trust that they will get enough heat. Clear and transparent communication will be crucial to building trust and confidence. Geoscience often faces difficulties with communication because the subsurface is difficult to conceptualise, and many geoscientific concepts are *"uncertain or unfamiliar to the wider public"* (Roberts *et al.,* 2021). Geologists can contribute to this by supporting clear assessment and communication of the information of interest to stakeholders, and by ensuring geoscientific data are accessible, transparent, and easy to translate for communities and stakeholders. For example, the UK Geoenergy Observatory projects have made all their data publicly available on their website (UKGEOS, 2024). There is a need to ensure that the public have the information that they want and need to be able to make informed decisions about minewater thermal schemes in their local area.

Geoscientists also need to be able to clearly communicate the range of career opportunities there will be for future geoscientists in the transition to net-zero (Gardiner *et al.,* 2023) Geoscience-related degrees have seen 43% decline in student numbers since 2014 (Williams *et al.*, 2024). This is similar to the problem raised by one participant of the low numbers of students choosing to train as heat pump installers, as well as the low capacity of these courses. The skills gap in heat pump installers is a recognised problem and could have significant implications for heat decarbonisation if not addressed (Brandford and Roberts, 2022; Cretu *et al.*, 2022). Careers that enable the transition to net zero whether its geoscience or heat pump installation, need to be highlighted as important roles for the future (Gardiner *et al.,* 2023).

Interviewees felt that minewater thermal projects could bring potential benefits to communities, such as potentially reducing heating bills for heat users, however specific details of other societal or community benefits were not discussed in depth during these interviews. Minewater thermal schemes have the potential to provide a wide range of benefits to communities, but these may not be realised if the needs or communities are not involved in project design and delivery (Roberts *et al.,* 2023). Indeed, due to the co-location of resource and settlements and the historical context of mining, minewater projects may work well as community-orientated developments (Roberts *et al.*, 2023). Interviewees raised concepts of community ownership of energy projects as potential benefit for communities, but details of such benefits were not specified. Energy projects that are community owned either through full ownership or through a co-operative have been found to increase the acceptability of such projects among local communities and can bring “more fairly distributed benefits and impacts” to society (Hogan *et al.,* 2022).

The need for minewater and other low-carbon heating projects to have nearby heat demand, was raised throughout the interviews i.e. local demand is critical for financial viability. At the same time, energy efficient homes and buildings require new approach to design and measures to be implemented to reduce heat demand. In addition, as raised by interviewees, demand for low-carbon heat is currently low, and changing heating systems is not a priority or a possibility for many. Even where there is demand for low-carbon heat, implementing solutions is difficult or not possible for most people due to finance constraints, shortage of installers, planning consent constraints, and other factors. Thus, mine water heat projects face similar challenges to decarbonising homes and buildings more generally, including need for top-down policy change (Lowes and Woodman, 2020) and support for bottom-up action and recognition of social drivers which do not exacerbate geo-demographic inequalities (Owen and Barrett 2020; Middlemiss *et al.* 2024).

3.4.3 Cost: minewater thermal costs and who pays?

Across the expert stakeholders interviewed for this research, the cost of minewater thermal projects was raised in three contexts: as a perceived disadvantage to minewater projects that require (expensive and risky) infrastructure to access to the subsurface; as a key piece of information required for developers to be able to consider and decide whether to deploy minewater thermal; and as a wider issue regarding heat decarbonisation in terms of who pays for it. Four interviewees perceived minewater thermal projects to be a solution that is more expensive and carries more financial risk compared to other low-carbon heating options, which is mostly due to high upfront costs for feasibility studies and drilling.

On the other hand, minewater thermal resources were also perceived to potentially be less costly than other geothermal heat solutions, due to the relative shallow depth and therefore lower cost of drilling relative to other geothermal schemes. Several participants agreed that minewater heat can be delivered with existing technology and skills in the workforce. However, there are opportunities for innovations to bring down the capital costs and risks associated with schemes (e.g., innovations to reduce the risk of missing a mineworking with a borehole should also reduce costs of drilling multiple boreholes). As with all novel technologies, innovation to address cost and risk reductions in an under-developed market can be seen as risky in itself, therefore further research is needed on how to incentivise enabling innovations to enhance market development. Thus, there are opportunities for geoscientists to work with other disciplines and stakeholders to develop and share good quality and efficient data collection and modelling to assess the geological conditions and co-location of supply and demand. Ultimately, such data, and well-validated models are essential to understand and reduce risks and cost, as well as identify opportunities for innovation and cost reduction. Open and transparent data and models will contribute to building trust.

Interviewees raised systemic economic and political issues such as the cost of electricity, cost of living crisis and cost of decarbonisation as challenges to heat decarbonisation more broadly, but which have ramifications for minewater thermal development. Interviewees raised concerns that the high cost of electricity and market volatility, at the time of the interviews, meant running low-carbon heating systems is more expensive than running a gas boiler for consumers, and could make many larger schemes, such as minewater, uneconomical to develop and operate. Not only does this maintain the status-quo of using gas boilers by making low-carbon heating systems unattractive to consumers, it is also related to high fuel poverty rates among households which rely on electric heating (Kerr and Winskel, 2021). Additionally, it has been shown that in countries where electricity is more affordable, sales of heat pumps are higher (EHPA, 2024). If low-carbon systems, such as minewater thermal, are to be implemented then they need to be done in such a way that will not exacerbate fuel poverty but reduce it.

3.4.4 Notable topics absent from the interviews.

There were three aspects commonly found in the minewater thermal literature that were not mentioned by any of the participants of this study. Firstly, none of the twelve stakeholders mentioned the use of existing minewater treatment works or passive drainage to harness heat from minewater. These can be accessed without the need to drill boreholes and would be developed in a similar way to the extraction of heat from surface water, rivers, or sewage and so are considered to be ‘low hanging fruit’ for minewater geothermal (Bailey *et al.*, 2016; Walls *et al.*, 2022). It is interesting that this resource was not mentioned by the participants of this study given its prevalence in the literature.

Secondly, Dickie *et al.* (2020) found the key concerns about minewater thermal raised by public participants include risk of subsidence and sinkholes caused by minewater schemes and concern regarding liabilities should something go wrong with these schemes. While, neither of these issues were specifically raised by interviewees in this study, stakeholders did raise questions around the regulation of minewater, uncertainty around ownership of heat, and liabilities in terms of maintenance of installed systems. Subsidence risk was not raised during these interviews, but understanding the geomechanics of a minewater system is very important as cyclical heating and cooling of the rock mass hosting a mine has been found to have an impact on the stability of the system (Hahn *et al.* 2018; Todd *et al.*, 2024).

Finally, environmental risks of minewater schemes were not discussed in these interviews. Community engagement from the UKGEOS project found that potential environmental impacts from the scheme were a concern of the local residents (Monaghan *et al.,* 2022b). Some environmental risks associated with minewater thermal schemes are common with other forms of shallow geothermal energy such as mobilisation of contaminants, through changes in water temperature, and the potential contamination of aquifers (McClean and Pedersen, 2023). Other risks are more minewater-specific such as, the introduction of oxygen into minewater causing mineral precipitation and a build-up of ochre (García-Gil *et al.* 2020; Walls *et al.*, 2021). The fact that these issues were not raised in the interviews could suggest that stakeholders felt these risks could be mitigated, or that there is a paucity of data from live minewater projects where any such risks have been realised.

3.5 Conclusions and implications for geoscience

We interviewed twelve expert stakeholders involved in the delivery of decarbonised heating and housing in order to establish their awareness of minewater thermal resources. Without an awareness of the potential of minewater technology and or other low-carbon solutions for decarbonising heat, these resources will not be considered early enough in the development of a project and therefore will be overlooked. The interviews highlighted the complexity of perceptions around the use of minewater thermal resources for heating and thermal storage, both technically and practically. Minewater thermal technology was generally viewed in a positive light by the stakeholders, but several concerns and potential barriers were raised. There was consensus that minewater thermal projects could be successful: if they are appropriately financed, regulated, constructed in the most optimal place and operated in a sustainable fashion, and in a way that builds trust amongst the end-users of heat. Cost was the challenge most often raised by interviewees, both the up-front capital cost and the operational costs including retail cost of electricity. Interviewees highlight the need to constrain the financial and technical risks for the construction and operation of minewater thermal schemes, in order to give developers confidence in the technology. The most significant risk for minewater thermal projects was perceived to be the pre-construction risks associated with determining the location and abandonment state of the mines, and the heat and fluid flow within them.

Interviewees perceived that the specialist geoscientific knowledge needed to deliver these resources was abundant in Scotland but also raised the spectre of a skills gap. Traditional geoscience roles, such as heat resource estimation, siting of potential minewater schemes, ground investigation, construction of boreholes, and research on minewater thermal storage, will be crucial for the development of a future minewater thermal industry. However, the geoscience community can play several other roles to help this industry to grow and address some of the wider issues raised by the participants of this study. For example, geoscientists need to be willing and able to collaborate with other disciplines like energy geographers, social scientists, and engineers to better understand heat demand and whether mines could meet the heating needs of an area, as well as considering other non-geological factors, such as historic and socio-economic contexts. Geoscientists must be equipped with skills to enable clear and transparent communication with relevant local stakeholders, local communities, and national and local government to help tackle wider issues that limit the development of minewater thermal and similar low carbon projects, such as the high retail cost of electricity. Additionally, the importance of future geoscience or net-zero careers needs to be communicated clearly to the next generation.

Finally, geoscientists must collaborate and communicate with each other to share data and findings to help reduce risks and costs of new projects and help the development of a future minewater thermal industry in the UK.

Similar to other geological contributions to net zero; while low carbon geological resources can help deliver a more sustainable future, simply 'doing the geoscience' will not work. Realising the potential for geoscience to contribute to society requires an understanding of the systems and interconnections that are needed to make the environment for geoscience technology uptake viable and practical. If key stakeholders who are involved in commissioning and delivering geological solutions to net zero are unaware of the potential of these technologies, or hold misconceptions about these technologies, the onus is on geoscientists to provide clear and transparent information to all relevant stakeholders.

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3.6 Spatial themes and link to following chapters

Chapter 3 raises several themes which also have a spatial element, such as potential of mine workings to be used as thermal storage, explored further in Chapters 4 and 5, and of heat demand, which will be explored in Chapter 6.

4. CHAPTER 4: Screening of mine shafts for future energy technologies: A case study from the Scottish Coalfields

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Author Contributions

This paper started as a report on the potential of mine shafts for use for CO_2 loop technology, led by I. Otalega in 2022 (supervised by NMB., ZKS., and GJ.). I. Otalega led the analysis and mapping for the CO_2 loop portions of the paper. Figures 4.3, 4.10, and 4.11 were created by I. Otalega, and Figure 4.2b was created by S. Flude. All other figures were created by K.B. Deeming. The study was later extended and the methodology developed to include thermal and potential energy technologies by K.B. Deeming (supervised by ZKS.).

KBD: conceptualization (equal), data curation (equal), formal analysis (equal), investigation (lead), methodology (equal), visualization (lead), writing – original draft (lead), writing – review & editing (equal); IO: conceptualization (equal), data curation (equal), formal analysis (equal), investigation (supporting), methodology (equal), writing – original draft (supporting); GJ: formal analysis (supporting), writing –review & editing (supporting); SF: formal analysis (supporting), writing –review & editing (supporting); ZKS: conceptualization (supporting), supervision (equal), writing – review & editing (equal); NMB: conceptualization (equal), funding acquisition (lead), supervision (equal), writing – original draft (supporting), writing – review & editing (equal). All authors have read and agreed to the published version of the manuscript.

Abstract

Abandoned mine shafts could be retrofitted for future energy technologies. We provide a high-level assessment of the potential for recorded mine shafts in the Scottish coalfields to be utilised for seven future technologies: geothermal heat extraction, thermal energy storage for waste heat and curtailed wind energy, gravity storage, underground pumped storage, compressed air energy storage, and CO_2 loop power generation. Screening is based on depth, volume and geographical criteria using GIS data from the Mining Remediation Authority. The theoretical resource was estimated for the 6,298 shafts that had information on depth and diameter. Heat extraction and thermal energy storage have potential capacities of 45 GWh and 33 GWh, respectively. Nearly 10 GWh of surplus electricity could be stored as heat in 288 mine shafts within 1 km of a primary substation. The capacities of potential energy storage technologies were considerably lower. We apply the concept of reserve and resource commonly used in extractive industries to illustrate the theoretical resource. However, many of these shafts may be inaccessible, have incurred damage that renders them unusable, or require significant engineering intervention. If this resource is to be realised as reserves, future work should focus on identifying and testing safe technological solutions.

4.1 Introduction

Abandoned mine shafts represent large volumes of subsurface void space that have the potential to be repurposed for future energy technologies. There is an increasing focus on the use of abandoned mine workings for the extraction of low-enthalpy heat for space heating and hot water in buildings (Verhoeven *et al.* 2014; Bailey *et al.* 2016; Banks *et al.* 2022; Monaghan *et al.* 2022a), as well as for use as thermal stores in district heating networks (Bracke and Bussmann 2015; Hahn *et al.* 2018; Bussmann *et al.* 2019; Hahn *et al.* 2019). Mine shaft thermal energy storage (MSTES) is also beginning to be investigated for capture and reuse of heat from, e.g., industrial processes or energy generation, including the opportunity to store curtailed wind energy and better balance power grids (Dassow *et al.*, 2024; Shipton *et al.,* 2024). Aside from thermal energy, mines have also been considered for other technologies which make use of potential energy to store electricity, such as gravity storage (Morstyn *et al.* 2019), pumped hydroelectric energy storage (Winde *et al.* 2017), and compressed air energy storage (Lutyński 2017). It has also been proposed that CO_2 closed-loop technology (Sun *et al.,* 2018) could take advantage of the low-enthalpy geothermal heat available in flooded mine shafts.

In Britain, technically and legally, the term 'mine workings' includes mine shafts, adits, roadways and worked seams, or panels. Mine shafts were sunk vertically and used to transport miners, coal, and equipment in and out of the mine via lifts, provide ventilation to the workings, and host pump infrastructure for the removal of groundwater. Mine shafts can be several hundred meters deep, and generally, more recent mines accessed deeper coal seams. Adits were tunnels connecting the mine to the surface, often on a hillside, and were used to either access the coal seams or to provide mine ventilation or drainage. Many worked seams will have collapsed over time, resulting in low permeability, with uncertain connectivity between the collapsed panels and the roadways that link them. In contrast, the roadways were often reinforced, especially the main ones, so they're more likely to remain open over time and could serve as preferential flow pathways. The shafts, being the main access points, are naturally connected to these main roadways, though some sections might still be closed off by fire doors or similar barriers. Upon abandonment, cessation of subsurface water management results in groundwater rebound and ingress of meteoric water, flooding the mined void spaces and facilitating water-rock interaction with exposed rock faces to create vast mine water reservoirs (Burnside *et al.* 2016b). These reservoirs are geothermally warmed by the natural flux of heat from the Earth. In British coalfields, this provides a median geothermal gradient of 24.1°C km^{-1} (Farr *et al.*, 2021).

Forecasting the properties of mine water reservoirs in roadways and worked seams can be difficult due to uncertainties in how (and in some cases, where) the mines were constructed, how they were treated upon abandonment, and how they may have collapsed or been infilled since abandonment (Andrews *et al.*, 2020; Walls *et al.*, 2021; Monaghan *et al.*, 2022a,b). The location of roadways and worked panels is not always reliable on mine abandonment plans (Banks *et al.,* 2022). The higher permeability roadways present a far smaller target for drilling than extensive worked panels. This can result in costly drilling campaigns and pump testing, though the costs can be reduced by repurposing boreholes drilled for ground investigation (Walls *et al.,* 2023).

In contrast, mine shafts are relatively straightforward: their location is generally well known, especially for the more recent and therefore deeper (higher volume) shafts. In Great Britain, the Mining Remediation Authority (called the Coal Authority until 2024) may hold records of how each shaft was treated during abandonment (i.e., whether it was backfilled, plugged or capped). Many shafts that have been capped or plugged have existing access points for Mining Remediation Authority monitoring, eliminating the need for drilling. Without such access points, drilling would be required to gain access, but only for a few tens of meters through the thickness of the cap and plug, which is far shallower than the deeper mine workings. The cost of evaluating a mine shaft's suitability for re-use is likely to be substantially less than that for underground mine roadways and worked seams. Open shafts also represent a simpler hydrogeological system than complex networks of roadways and worked seams. In effect, an unfilled shaft can be treated as a large 'tank' of water rather than a series of interconnected aquifers with variable porosity, albeit a tank that may be connected to those wider workings. As such, a mine shaft is unlikely to require pumping-tests to establish near-field flow properties. Overall, this means that the capital outlay at the site and ground investigation stage is likely to be lower for repurposing shafts than for mine roadways and worked seams, and hence, they may provide a more attractive investment target.

Large underground voids have been proposed for use in several energy storage technologies. In this paper, we perform an initial high-level screening of mine shafts which could, in principle, be suitable for the application of such technologies. Seven proposed technologies (Table 4.1) have been considered in this screening process, which can be split into two categories: those which extract or store thermal energy (heat) and those that store electrical energy as potential energy. Storage of chemical energy in the form of fluids such as hydrogen has not been considered here: such storage requires containment of these fluids, which is likely to be very difficult in mine shafts that are typically connected to a wider network of mine roadways and worked seams. While we are assessing all seven technologies, it's important to clarify that, MRA currently permit only heat extraction and storage within mine workings. The remaining five technologies could become relevant options in the future as new technologies/engineering solutions are proven to be safe and effective. Demonstrating the scale of the opportunity for energy technologies in mine shafts should help to justify investment in derisking and reduce the cost of these technologies.

We used data that can be requested from the Mining Remediation Authority (MRA) by any member of the public (though which may be subject to a licence agreement and fee), and that are available to academic researchers through the Digimap service (Edina Digimap, 2025a). We use the mine entries database from the Mining Remediation Authority (MRA) the Scottish coalfields (MRA, 2022) along with geothermal gradients calculated for the Scottish coalfields by Farr *et al.* (2021). Shafts were screened based on the technological requirements of the seven different future energy technologies, which are described below.

Table 4.1: Future energy technologies that could utilise mine shafts sorted by thermal energy technologies and electrical (potential) energy technologies.

Technology	How does it work?	References
Thermal		
Mine water heat extraction (mine water geothermal)	Heat is extracted from the mine water using heat exchangers and boosted using heat pumps. Heat is recharged geothermally, limiting the rate at which it can be extracted.	Walls *et al.* 2021; Monaghan *et al.* 2022a
Mine water thermal energy storage (for waste heat or solar heat)	Heat to heat – surplus heat on the surface is transferred into the mine where it is stored until it is needed.	Hahn *et al.* 2019; Whittington *et al.*, 2023; Perez-Silva *et al.* 2022
Mine water thermal energy storage (curtailed wind - electricity)	Electricity to heat – surplus electrical energy is used to heat the water in the mine shaft, and that heat can be extracted later.	Dassow *et al.*, 2024 Shipton *et al.,* 2024
Electrical		
Gravity storage	Stores electricity as potential energy of a suspended weight which is released down the mine shaft to recover electrical energy.	Morstyn *et al.* 2019; Hunt *et al.* 2023
Underground Pumped Hydroelectric Energy Storage (UPHES)	Stores electricity as potential energy of water – works like other forms of pumped hydro.	Winde *et al.* 2017; Menéndez *et al.* 2019; Álvarez *et al.* 2021

Compressed Air Energy Storage (CAES)	Stores surplus electricity by compressing air, which is stored in underground voids. When the electricity is needed the compressed air is released through a turbine.	Lutyński 2017; Menéndez *et al.* 2019; de Prado *et al.* 2021
CO_2 loop technology	Generates a thermosiphon by heating CO_2 which enables the circulation of a carrier fluid, without a mechanical pump.	Freifeld *et al.* 2013; Sun *et al.* 2018; Carro *et al.* 2021

Mine water heat extraction and thermal storage. The warm water within flooded mine workings can be used as a heat source for heat pumps (Banks *et al.,* 2019). The temperature of mine water remains stable (within a couple of degrees) year-round, meaning the coefficient of performance (COP) of mine water heat pumps will be greater than air source heat pumps, especially during winter months (Bailey *et al.* 2016). Heat pump COP is influenced by end-use demand temperature and the temperature of the source, with warmer mine water increasing COP (Banks, 2012; Harrison *et al.,* 2024). Thermally spent water can be treated and discharged to a surface water body or returned to a separate location in the mine, in which case any 'thermal break through' to pumped boreholes should be mitigated by maximizing tortuosity of prospective flow paths and increasing opportunity of returned water to be geothermally reheated. Open loop systems have successfully been deployed in a single mine shaft, albeit at a relatively small scale, using a 20 kW heat pump and a sealed shell-and-tube heat exchanger (Athresh *et al.* 2015; Burnside *et al.,* 2016a; Al-Habaibeh *et al.* 2018). Closed loops can also be circulated within a mine shaft (Rudakov and Inkin, 2022), though this is less efficient at extracting heat.

Depending on the level of heat extraction and size of the mine water reservoir, extracting heat may eventually lower the temperature of the entire mined volume. It is therefore desirable to thermally balance the system by providing cooling as well as heating, or by recharging with heat from surface sources such as solar thermal or industrial waste heat, which is known as Mine Thermal Energy Storage (MTES; Bracke and Bussmann, 2015; Hahn *et al.,* 2018; Bussmann *et al.,* 2019; Hahn *et al.,* 2019; Perez-Silva *et al.,* 2022). It has also been proposed that surplus electricity from wind energy could be used to generate heat that could be stored in mine shafts (Dassow *et al.*, 2024). As an example, to maintain power grid stability, 13% of the annual electricity production by Scottish wind farms was curtailed in 2021 (Renewable Energy Foundation, 2022). Instead of curtailing electricity production, such excess wind power could be stored as thermal energy in a mine shaft. For a mine shaft to be considered for geothermal heat extraction or MSTES, using the technologies discussed here, it must be flooded. To act as a thermal store, the larger the volume of water, the greater the storage capacity. Heat is inefficient to transport, even within highly insulated district heat networks. So, for both geothermal heat extraction and thermal storage, and heat customers (and for thermal storage sources of waste heat) should be close to the store (Ma *et al.,* 2009; Jung *et al.,* 2022). For the purposes of this screening, we consider a 1 km radius as adequately close and, therefore, have applied a 1 km buffer to heat sources and grid connections. Todd *et al.* (2024) examined the risk of subsidence associated with the re-use of mine workings for heat extraction and storage. The risk of subsidence is greatest closer to the surface, so we used a depth value of 50 m below ground level (bgl) to screen out the shallowest shafts, which will be associated with the shallowest mine workings and, therefore, greater risk.

Gravity Storage involves using surplus electricity to raise a weight within a shaft, then generating electrical energy when it is dropped. A GIS screening process was undertaken by Morstyn *et al.* (2019) for gravity storage in mine shafts in the English Midlands. They considered the diameter and depth of the mine shafts and the potential energy that could be generated from dropping and raising a 3,000-tonne weight in the mine shafts. They found 340 shafts in their study area that had the potential to store over 1 MWh, amounting to a total of 0.804 GWh of energy storage in the midlands alone. This technology requires shafts to be accessible, not filled in, and dry (Morstyn *et al.,* 2019). Morsytn *et al.* (2019) acknowledge that the flooding status of mine shafts would have to be considered on a case-by-case basis, and that many shafts are already flooded, making them unsuitable. Morstyn’s analysis is, therefore, an upper estimate of the overall potential storage capacity that could be provided by gravity storage technology.

Underground pumped hydroelectric energy storage stores electricity in the form of potential energy of water (Winde *et al.* 2017; Menéndez *et al.* 2019, Álvarez *et al.* 2021) in a similar way to traditional pumped hydro storage systems; water is pumped to a storage site at elevation during times of low electricity demand, and then released to flow to lower elevation levels, driving turbines and generating electricity, when required. However, traditional pumped hydro storage is limited by topography, land use, and public acceptance; barriers that could be overcome by installing the whole system underground (Pujades *et al.* 2016; Menéndez *et al.* 2019). For *underground pumped hydroelectric storage,* upper and lower reservoirs are constructed within the mine workings (the upper reservoir may be on the surface), and water is transferred between the two reservoirs via the mine shaft. The storage capacity is determined by the volume of stored water, and the height difference between the upper and lower reservoirs (Menéndez *et al.* 2019). There can be a greater difference in hydraulic head between the two reservoirs than in traditional pumped hydro, meaning that smaller volumes of water can generate the same amount of electricity (Pujades *et al.* 2016). Therefore, having deep mine shafts with large volumes will mean that more energy can be stored.

Compressed air energy storage (CAES) also uses potential energy, but this time of compressed air instead of water. Electricity is used to compress large volumes of air during periods of low demand, which is then stored in underground voids or large tanks, and it is released to generate electricity by driving a turbine (Menéndez *et al.* 2019; de Prado *et al.* 2021). CAES systems need a large volume; for example, to store 8 hours of electricity, a 300 MW CAES system needs approximately. 620,000 m^3 of storage space (Menéndez *et al.* 2019). Given the nature of the technologies, both UPHES and CAES require mines which are not completely flooded (Menéndez *et al.* 2019). A key future engineering challenge is isolating these void spaces from the rest of the mine workings.

CO_2 closed-loop technology (Freifeld *et al.* 2013; Sun *et al.* 2018; Carro *et al.* 2021) involves heating CO_2 to a desired level to create a thermosiphon that enables system carrier fluid circulation without the need for a mechanical pump. This can be used for both low carbon heat and power generation. There is also potential to create a more efficient system by increasing the length of the closed loop by utilizing a pair of connected shafts. This technology needs a temperature differential of 15°C. Therefore, the bottom temperature of the shaft must be at or above 22°C to give 15°C above surface mean air temperature for Scotland.

4.2 Methodology

The Mining Remediation Authority (MRA) holds much of Great Britain's available historical coal mining data and can provide access to this legacy information under license (MRA, 2017). The dataset used in this analysis is the mine entries data set, for the Scottish coalfields, provided by The Mining Remediation Authority (MRA, 2024c) under a Non-Commercial Use License. The dataset is a GIS shapefile which included point locations of mine entries, depth, diameter (measured and assumed), mineral mined, shaft name and occasionally colliery name. Table 4.2 shows the data fields used in this analysis and the data coverage of each. A full list of the data fields in this dataset and the data coverage of each can be found in Appendix 10.3. Information such as year of shaft construction and abandonment; information on abandonment state; shaft lining (e.g., concrete, brick, no lining); presence, material and depth of backfill; and flooding status are not included within this dataset. More information for individual shafts may be available from the Mining Remediation Authority on a case-by-case basis.

The Scottish Coalfields are split into twelve Mine Water Blocks (MWB) by MRA (Figure 4.1). These are considered to be distinct, unconnected hydraulic units based on information on hydrogeological interconnection (e.g., connected by mine workings, e.g. adits driven for emergency escape purposes) or barriers (e.g., fault zones or unworked coal), with most coalfields comprised of several MWBs (Farr *et al.*, 2021; Jack *et al.* 2023).

Table 4.2: Data fields used in this analysis from the Mining Remediation Authority mine entries dataset (MRA, 2022).

Data field	Description from MRA guidance (MRA, 2022)	Data field coverage
TYPE	Mine entry type. Denotes if mine entry is a shaft or an adit. (for this dataset, all of the entries were shafts)	100%
MI_CODE	Mineral worked. Most are coal but the Mining Remediation Authority also holds records for other minerals in cases where they were worked with the coal or close to the coal seams. Other minerals include limestone, ironstone, and oil shale.	100%
DEPTH	Depth of mine entry in metres from surface. The Mining Remediation Authority will only provide the depth of a mine entry where this is known.	32%
SHFT_DM	Actual diameter of mine entry in metres.	3%
ASUM_DM	Assumed shaft diameter: Where information about the diameter of a shaft is not known it will be assumed. The assumption will be based upon comparison with other shafts in the vicinity, the likely date it was sunk and any other relevant information.	98%

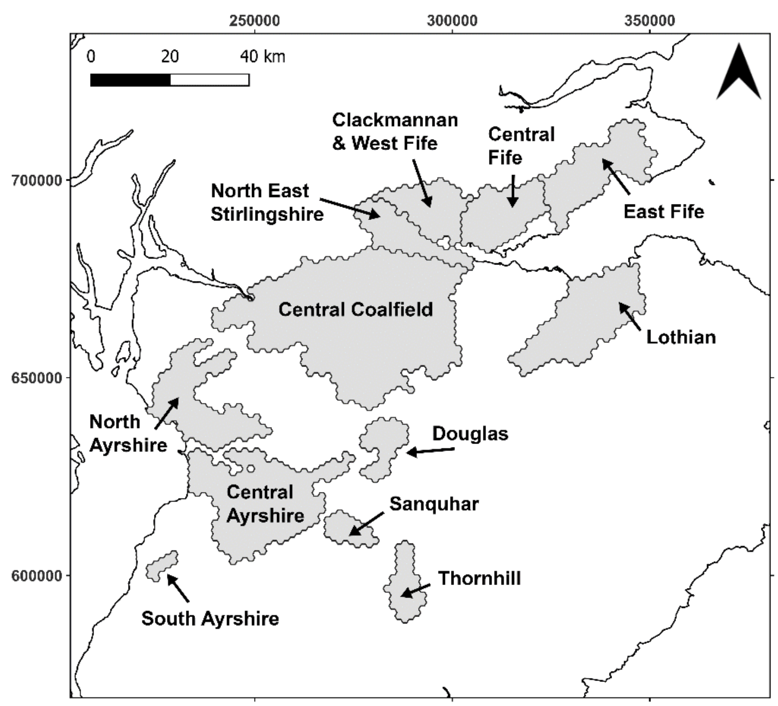

Figure 4.1: Mine Water Block (MWB) units in the Central Belt of Scotland designated by the Mining Remediation Authority (MWB GIS data from Farr et al., 2021).

4.2.1 Screening

The data were screened using QGIS software based on criteria from two different categories for each of the future energy technologies: the characteristics of the mine shafts and the characteristics of the local geography.

Mine shaft characteristics:

- Vertical shaft depth (MRA data)
- Diameter of the shaft (MRA data)
- Temperature at the base of the shaft (calculated using data from Farr *et al.*, 2021)
- Volume of the shaft: calculated using depth and diameter data.

For diameter, two values are presented in the dataset: *assumed diameter* and *(actual) shaft diameter*. The actual diameter was used when it was available, but otherwise the assumed diameter was used to calculate the volume, using the equation for the volume of a cylinder:

$$V = \pi r^2 h$$

Where V = volume (m^3), r = radius (m), and h = height = depth of the shaft (m).

The temperatures at the base of the mine shafts were calculated using the average MWB geothermal gradients from Farr *et al.* (2021) using a GIS shapefile available from data.gov.uk (2022) and a mean surface air temperature of 7.4°C. Equilibrium temperatures are measured in unpumped boreholes and are thought to adequately reflect in situ temperatures (Farr *et al.*, 2021). No geothermal gradient was given for Central Ayrshire MWB, therefore a geothermal gradient of 25°C km^{-1} was used based on reported mine water temperature measurements taken at the Barony and Killoch collieries during their operation (Burley *et al.*, 1984). It should be noted that operational mines are likely to have been cooler than the in-situ geothermal gradient would suggest, due to ventilation of the mine.

Geographic location factors:

- Proximity to heat sources
- Proximity to electricity grid connection
- Proximity to urban/suburban areas

The proximity to urban and suburban land cover was analysed using the UK Centre of Ecology & Hydrogeology (UKCEH) Land Cover Map 2020 (UKCEH, 2020), obtained from Digimap online map and data delivery service operated by the EDINA national data centre for UK Higher and Further Education establishments. The proximity to heat sources was analysed using Energy Supply Point data from the Scottish Government (2024d). This provides data on the locations of existing and planned sources of both electrical and heat energy. For the purposes of this screening only heat sources will be included: energy from waste (n=21), ground source heat pumps (n=3), and water source heat pumps (n=3). All these sources are classified as being ‘Large (over 1 MW)’.

Data on the location of electricity grid infrastructure is held by the network operators. For Central and Southern Scotland, which covers the whole Scottish coalfields area, the electricity network is operated by Scottish Power Energy Networks (SP Energy Networks, 2024). This data can be transferred as a shapefile into QGIS via the SP Energy Networks Open Data Portal. For this analysis the locations of primary substations were used (n = 384). These substations are categorised based on their capacity to have new distributed generation join the network. Of the substations in the dataset, 97% are classified as red, meaning they had insufficient capacity for new connections.

Table 4.3 summarises the screening criteria applied to the mine shafts in this study. We calculate the potential energy or thermal energy that could be generated or stored across the selected mine shafts for each technology, using the following equations.

Heat in place (for heat extraction and thermal storage) can be calculated using this equation:

$$H = \left[\rho_w C_p\right] \cdot V \cdot (\Delta T)$$

where H = heat energy (J), ρ_w = density of water (kg m^{-3}), C_p = specific heat capacity of water (J kg^{-1} K^{-1}), V = volume of aquifer, or in this case mine shaft (m^3), ΔT = temperature change (Adapted from Downing and Gray 1986). This equation gives the heat energy in joules which is then converted to MWh. For this analysis, a temperature change (ΔT) of 10°C was used, after Gillespie *et al.* (2013). This is the total heat stored within the mine shaft and is therefore an upper bound on the heat that can be extracted. Note that for practical considerations around economics and thermal efficiency of potential schemes involving MSTES or minewater heating / cooling, we include criteria which screens for waste heat sources (i.e., heat generated from industrial processes or energy production that is not currently captured) and complimentary heat sources (i.e., heat that is being deliberately produced for supply, and could be used in combination with minewater to expand the heat network) within 1 km of a mine shaft.

Potential energy for gravity storage is:

$$E = mgh$$

where E = energy (J), m = mass (kg), g = acceleration due to gravity (m s^{-2}), and h = height (m). A mass of 3,000 tonnes (3,000,000 kg) was used after Morstyn *et al.* (2019), and the height was considered to be the depth of the mine shaft.

Potential energy for pumped hydroelectric storage is calculated using:

$$E = \rho g h V \eta$$

where E = energy (J), ρ = density of water (kg m^{-3}), g = acceleration due to gravity (ms^{-2}), h = hydraulic head (height) (m), V = volume of water in storage reservoir, and η= efficiency of the turbine and generator system. For this technology the volume depends on the size of the upper and lower reservoirs, which are separate from the mine shaft – the mine shaft is simply the drop that the water goes down to generate the electricity. For this analysis the full volume of the shaft is used and an efficiency of 80% is assumed.

Potential energy for compressed air storage is calculated using:

$$E = \ p_B V_B ln \frac{p_A}{P_B} + (p_B p_A) V_B$$

where E = energy (MJ), p_A = ambient pressure (1 bar = 0.1 MPa), p_B = pressure in the storage vessel (MPa), V_B = volume of storage vessel (m^3). Lutyński (2017) reports a pressure range of 4.6 – 7.5 MPa, so for this analysis, a pressure of 7 MPa (70 bar) has been used.

CO_2 loop technology. Calculating the energy stored using this technology requires complex computer modelling beyond the scope of this analysis, see Freifeld *et al.* (2013), Sun *et al.* (2018) and Carro *et al.* (2021).

Table 4.3: The screening criteria used for each of the seven future energy technologies, split by mine shaft characteristics and geographic factors.

<table>
<tr><th colspan="2" rowspan="3">Criteria</th><th colspan="7">Future Energy Technologies</th></tr>
<tr><th colspan="2">Thermal energy storage</th><th rowspan="2">Heating and cooling</th><th rowspan="2">Gravity storage</th><th rowspan="2">Underground Pumped Hydroelectric Energy Storage (UPHES)</th><th rowspan="2">Compressed Air Energy Storage (CAES)</th><th rowspan="2">CO_2 Loop Technology</th></tr>
<tr><th>Heat</th><th>Curtailed electricity</th></tr>
<tr><td rowspan="4">Mine shaft characteristics</td><td>Mine shaft depth
(m bgl)</td><td colspan="2">The deeper the shaft, the larger the volume - at least 50 m bgl.</td><td>Deeper mines are warmer -at least 50 m bgl.</td><td colspan="2">The greater the distance between upper and lower reservoirs/weight position the better -longer drop.
At least 500 m bgl</td><td>The greater the depth, the larger the volume.
At least 500 m bgl</td><td>At least 100m bgl</td></tr>
<tr><td>Temperature at base of shaft (°C)</td><td colspan="2">n/a</td><td>Higher temperatures mean a greater COP for the heat pumps</td><td>n/a</td><td>n/a</td><td>n/a</td><td>At least 22°C</td></tr>
<tr><td>Shaft Diameter (m)</td><td>n/a</td><td>n/a</td><td>n/a</td><td>At least 3.5 m wide to accommodate the suspended weight (Morstyn et al., 2019).</td><td>n/a</td><td>n/a</td><td>n/a</td></tr>
<tr><td>Volume (m^3) (calculated)</td><td colspan="2">At least 1000 m^3</td><td>n/a</td><td>n/a</td><td colspan="2">Large - at least 10,000 m^3</td><td>n/a</td></tr>
<tr><td rowspan="3">Geographic factors</td><td>Proximity to urban areas</td><td colspan="3">Yes – needs local heat demand / supply to support business case of any development</td><td colspan="4">No</td></tr>
<tr><td>Proximity to heat source</td><td>Yes - to supply heat for storage – within 1 km.</td><td>No</td><td>Additional heat source not necessary but could make heating system more efficient – within 1 km.</td><td colspan="4">No</td></tr>
<tr><td>Proximity to grid connection</td><td>Yes - to power the heat pumps</td><td>Yes – to charge the system with surplus energy</td><td>Yes - to power the heat pumps</td><td colspan="4">Yes - to charge or discharge the system. Within 1 km of a primary substation.</td></tr>
</table>

4.3 Results

4.3.1 Summary of shaft data available for Scottish coalfields: initial screening

The GIS shapefile obtained from MRA contained 17,896 mine entries (shafts), out of which: 17,389 (97%) were used for coal mining, with the rest used for ironstone, limestone or oil shale. 16,914 (94%) were located within MRA Mine Water Block (MWB) boundaries. 6,298 (35%) of those within the MWBs contained shaft depth data (Figure 4.2). The Central Coalfield MWB has the most recorded shafts with depth data (3,297), followed by the Lothian MWB (505). No shafts with depth data were recorded in the Thornhill MWB. The deepest shafts, 921 and 932 m bgl, are found in the Lothian MWB. The mean depth of mine shafts with data is 72 m bgl (± 83.4 m – standard deviation), and the median depth is 45 m bgl (Figure 4.2b). Approximately 79% of the shafts are shallower than 100 m below ground level (bgl), with only 2.6 % exceeding 300 m bgl. The assumed diameter was available for 6,101 of the 6,298 shafts that had depth data, but (actual) shaft diameter values were only listed for 313 entries. Only two of the 6,298 shafts with depth data had neither assumed or actual diameter data. Assumed diameter ranged from 1.5 to 7 m and actual shaft diameter ranged from 0.5 to 8 m. Figure 4.3 depicts temperatures across the Scottish MWBs, at 100 m bgl, 500 m bgl, 700 m bgl, and 900 m bgl using the equilibrium temperatures from Farr *et al.* (2021) and have been populated with the distribution of shafts across the MWBs. The Central Coalfield has the highest geothermal gradient among the Scottish MWBs of 29.8°C km^{-1} (Farr *et al.*, 2021).

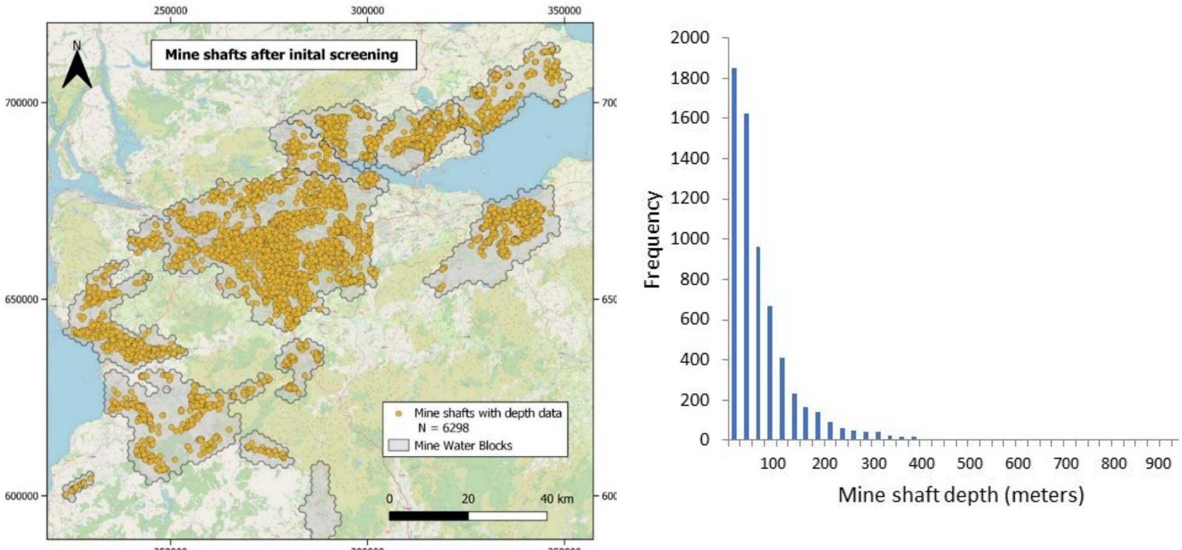

Figure 4.2: a) Mine shafts that meet the initial screening criteria: within a MWB and have depth data. b) The frequency distribution of mine shaft depth for the full dataset (created by S. Flude). In this and all subsequent maps the shaft data are (MRA, 2022) © The Mining Remediation Authority (all rights reserved) and mine water block boundaries from Farr et al. (2021) and the base map is from Open Street Map (2024) (CC BY-SA). ©

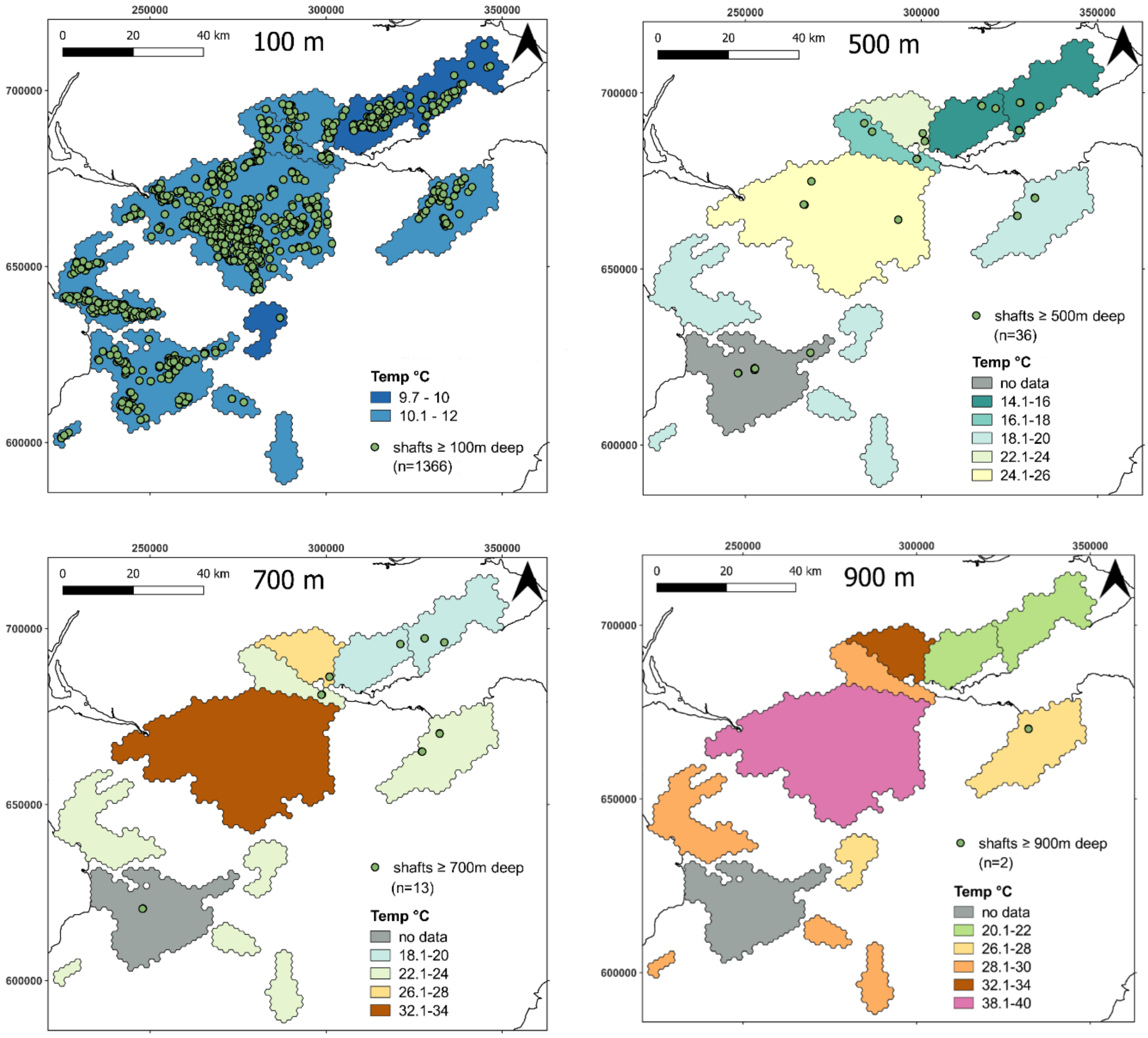

Figure 4.3: Mean equilibrium temperatures for Scottish MWBs at a) 100 m bgl, b) 500m bgl, c) 700m bgl and d) 900m bgl. Green dots represent shafts equal to or exceeding the depth in the relevant figure. Equilibrium temperatures for each MWB after Farr et al. (2021). Figures created by I. Otalega.

4.3.2 Screening results for future thermal energy technologies

4.3.2.1 Mine water heat extraction

Minewater heat extraction had the broadest selection criteria, any shaft with a depth greater than 50 m, giving 2,947 mine shafts across eleven out of twelve MWBs which met the criteria (Figure 4.4). The total resource of these shafts is an energy capacity of 45.1 GWh based on a temperature change of 10°C. Figure 4.5 shows the results of additional screening for the concept of reheating thermally spent water prior to reinjection using surplus energy from waste plants: 54 shafts across 4 MWBs fall within 1 km of an energy from waste plant. Large heat pumps were included in the analysis, but none were located within 1 km of a > 50 m bgl deep shaft. For these 54 shafts the energy capacity is 2.18 GWh based on a temperature change of 10°C. These estimates are for the heat in place within the mine shafts alone. Although many shafts will be connected to large underground reservoirs, this was not included in this initial screening analysis.

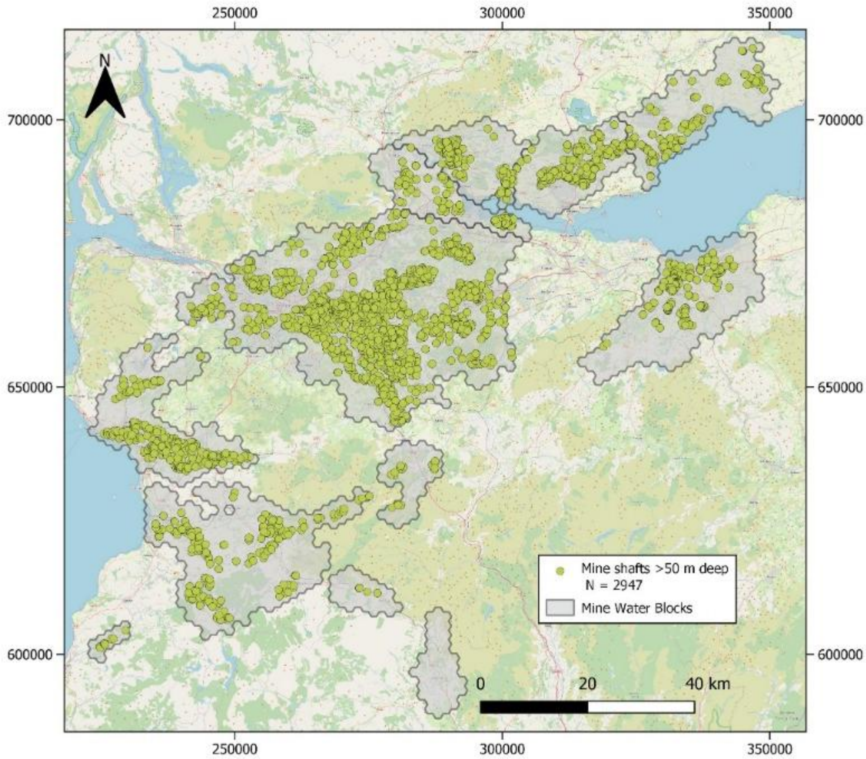

Figure 4.4: All Scottish mine shafts with a depth greater than 50 m bgl, that lie within the MWB boundaries.

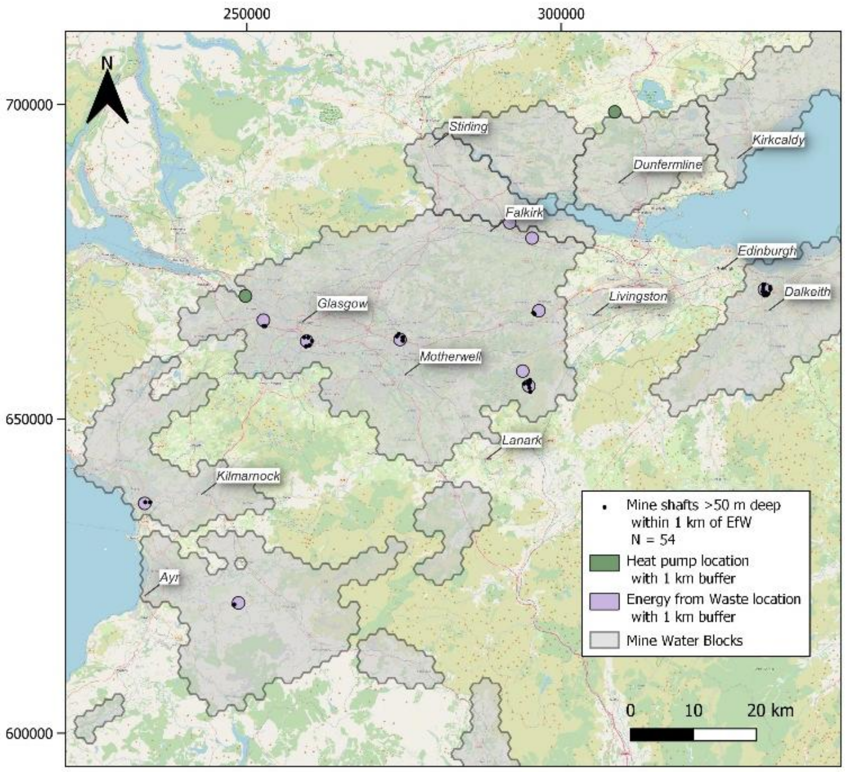

Figure 4.5: Mine shafts (small black circles) with a depth greater than 50 m bgl within 1 km of an energy from waste plant (purple circles). Please note no mine shafts >50 m bgl were within 1 km of a heat pump site (green circles).

4.3.2.2 Results for Thermal Energy Storage technologies

Figure 4.6a shows mine shafts that are > 50 m deep with a minimum volume of 1000 m^3 (Section 2.3). The resulting 1035 shafts which meet these criteria were distributed across 10 of the 12 MWBs. Shaft depths range from 104 to 931 m bgl, and shaft volumes range between 1001 and 38,966 m^3. These 1035 shafts have a total estimated energy storage capacity of 33.8 GWh, based on a ΔT of 10°C. Of these shafts, 28 are located within 1 km of a heat source (Figure 4.6b), across four MWBs, with a total energy storage capacity of 2.03 GWh. As before, the heat source locations are energy from waste plants, and no mine shafts were within 1 km of an industrial heat pump.

Figure 4.7 shows the results of screening for heat storage from curtailed wind or surplus electricity. A total of 288 mine shafts, across eight MWBs, met the depth, volume, and geographic criteria (within 1 km of a primary substation). Shaft depths range from 54 m to 879 m bgl, and shaft volumes range between 1,001 m^3 and 31,851 m^3. These shafts have an estimated total heat energy storage capacity of 9.92 GWh based on a ΔT of 10°C. The range of storage capacity in individual shafts is between 0.012 GWh and 0.37 GWh.

Table 4.4: Summary of the number of shafts suitable for utilisation by thermal energy technologies (according to the appropriate screening criteria) and their total energy capacity. Contains data from MRA (2022).						
Criteria (Based on a ΔT of 10°C)	**Heat extraction**		**TES (heat)**		**TES (electricity)**	
	Number of. shafts	*Energy (GWh)*	*Number of. shafts*	*Energy (GWh)*	*Number of. shafts*	*Energy (GWh)*
Total shafts	2947	45.1	1035	33.8	1035	33.8
Geographic factors	54	2.18	28	2.03	288	9.92

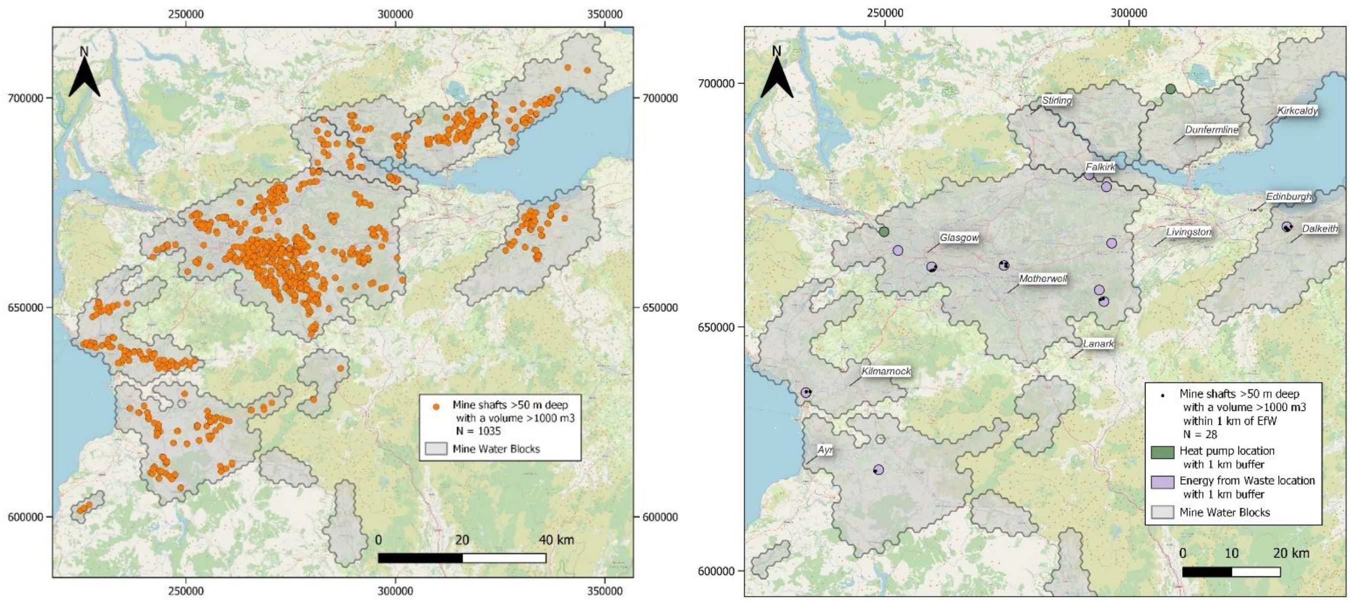

Figure 4.6: Mine shafts suitable for thermal storage that have a) depth of over 50 m bgl deep, a volume greater than 1000 m^3 and b) that are within 1 km of an energy from waste heat source (N=28). n.b. no mine shafts meeting the depth/volume criteria were within 1 km of an industrial heat pump.

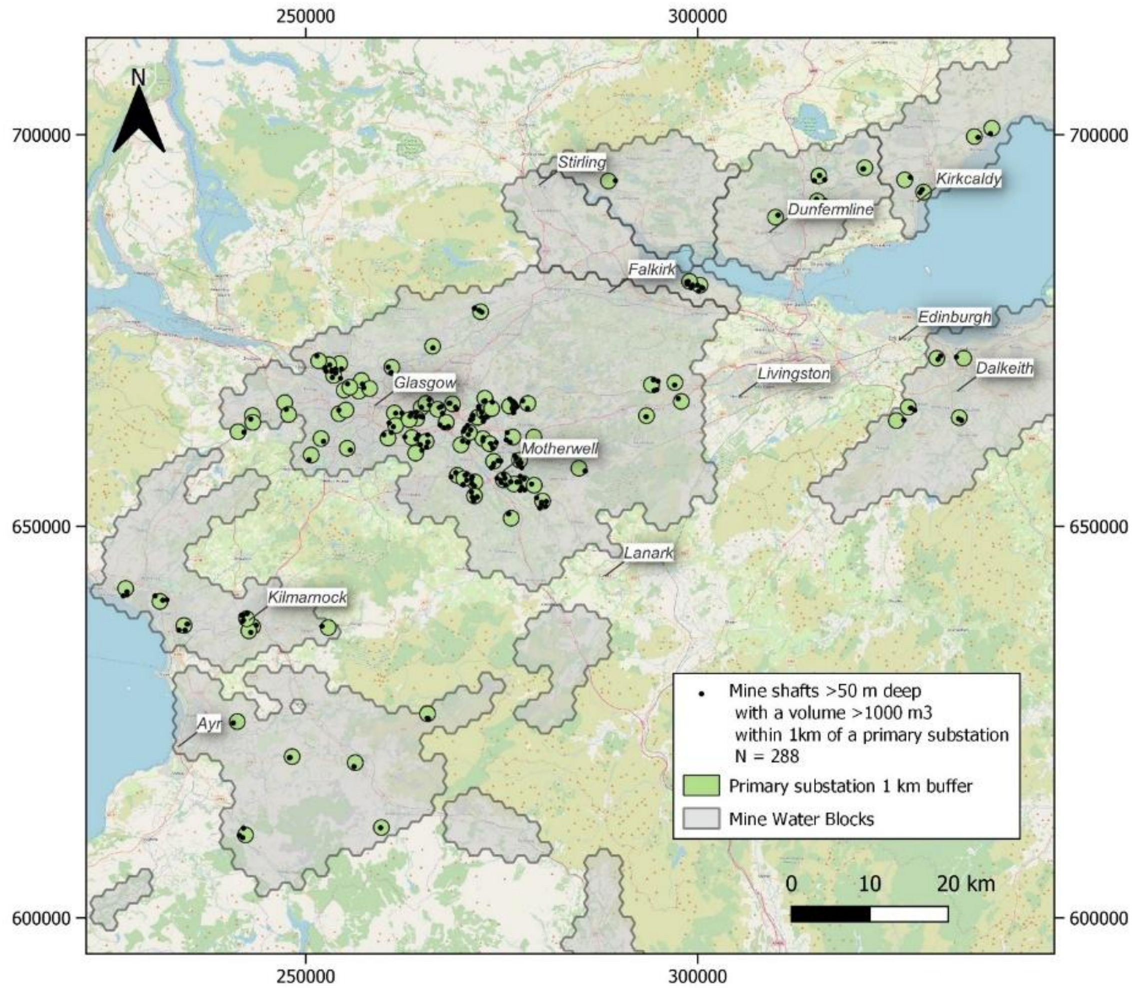

Figure 4.7: Mine shafts for heat storage from curtailed wind or surplus electricity: over 50 m bgl deep, a volume greater than 1000 m^3 and are within 1 km of a primary substation (N=288). The italic labels show the locations of towns and cities, to provide context. Contains data from MRA (2022)

4.3.2.3 Screening results for future potential energy storage technologies

Figure 4.8a shows 36 mine shafts which have depth > 500 m and diameter > 3.5 m. These shafts have the potential to store 0.2 GWh of energy, if used for gravity storage. Figure 4.8b shows the 19 mine shafts which meet the criteria for underground pumped hydro storage and compressed air energy storage, where depth > 500 m and volume > 10,000 m^3. All three of these technologies require an electricity grid connection. Eight of these mine shafts are within 1 km of a primary substation, satisfying the respective criteria for all three technologies (Figure 4.9). These eight are distributed across five mine water blocks, with a depth range of 515 to 879 m bgl, a diameter range of 4.2 to 7.3 m, and a volume range between 11,347 and 31,851 m^3. If all 8 shafts were all used for a single storage approach, they could provide a total energy storage capacity of 0.05 GWh for gravity storage, 0.26 GWh for UPHES, and 1.02 GWh for CAES. Table 4.5 shows a summary of the number of shafts and the energy capacity for each of the three potential energy technologies given the different criteria.

Table 4.5: Summary of the number of shafts suitable for potential energy storage technologies (according to the appropriate screening criteria) and their total energy capacity. Contains data from MRA (2022).						
Criteria	**Gravity storage**		**UPHES**		**CAES**	
	Number of. shafts	*Energy (GWh)*	*Number of. shafts*	*Energy (GWh)*	*Number of. shafts*	*Energy (GWh)*
Total shafts	36	0.20	19	0.69	19	2.66
Geographic factors	8	0.05	8	0.26	8	1.02

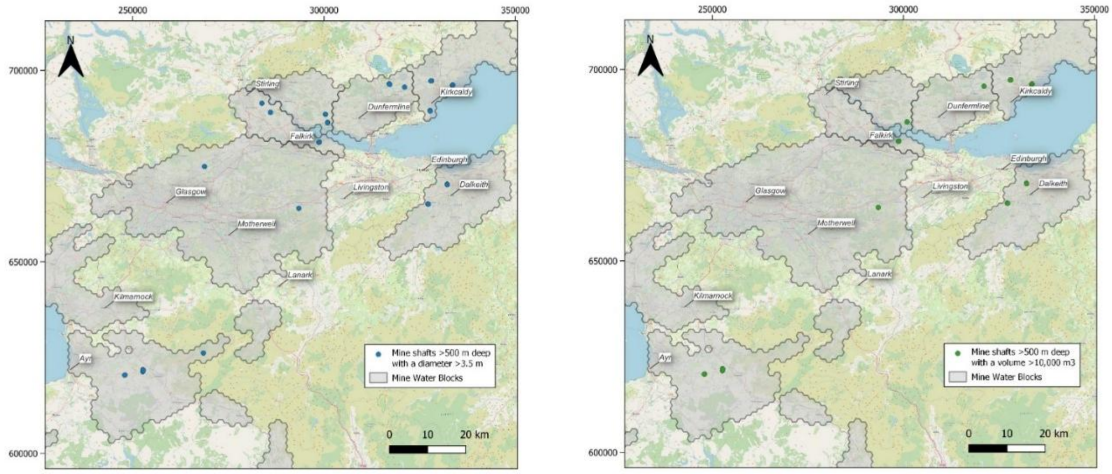

Figure 4.8: Mine shafts suitable for potential energy storage. a) Shafts with a depth greater than 500 m bgl and a diameter greater than 3.5 m (N = 36) and b) a volume greater than 10,000 m^3 (N = 19), that lie within the MWB boundaries.

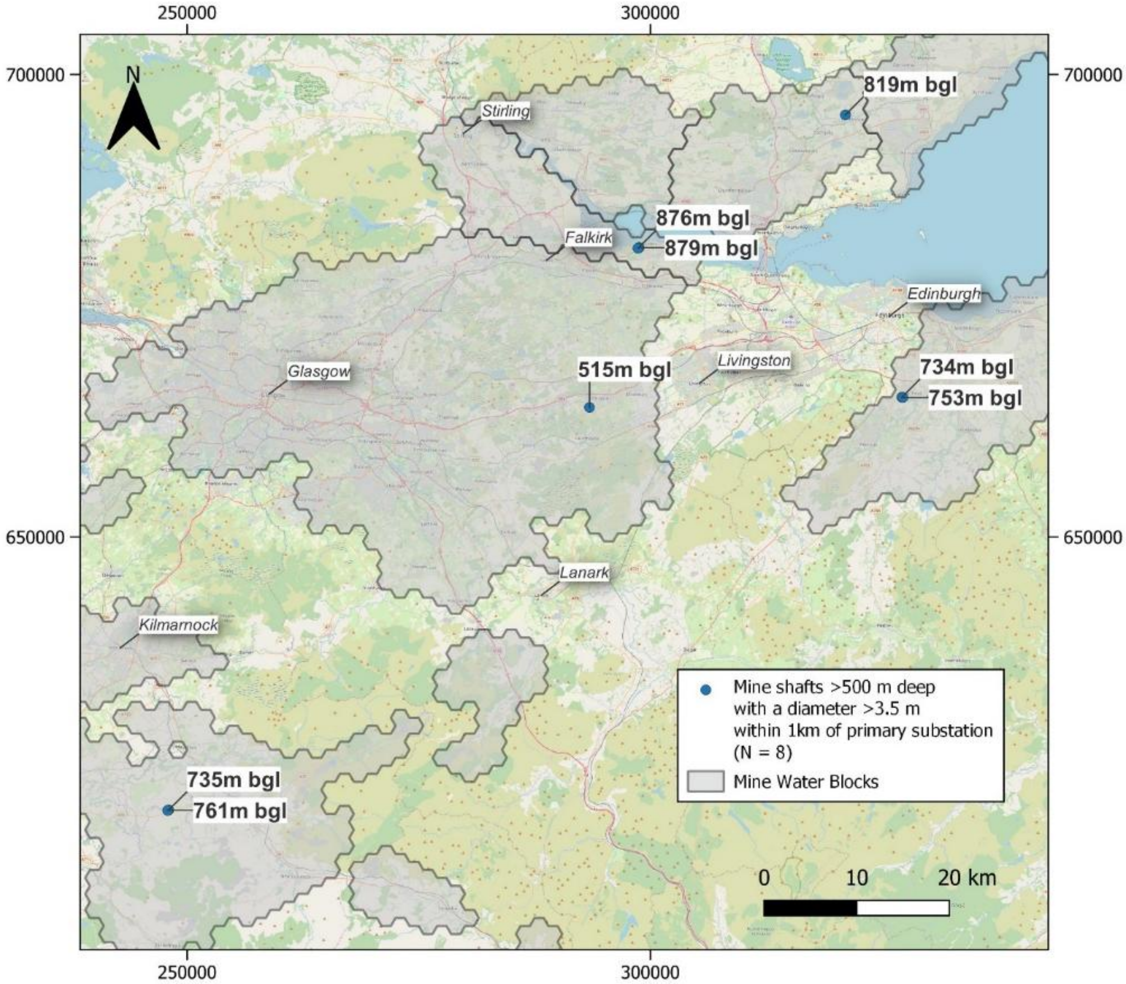

Figure 4.9: Mine shafts with a depth greater than 500 m bgl and a diameter greater than 3.5 m that are within 1 km of a primary substation (N = 8). All 8 mine shafts have a volume greater than 10,000 m^3, the bold labels show the depths of the mine shafts. Contains data from MRA (2022).

4.3.2.4 3.3.1 Results for CO2 loop technology

For this technology, shafts were screened using bottom temperature ≥ 22°C to account for a differential of 15°C above surface air temperature. This results in 28 eligible shafts, across seven MWBs, which have a depth range of 488 m bgl to 931 m bgl (Figure 4.10). Due to the novel nature of this technology, the location relative to urban and suburban land cover was added as a screening criterion to consider prospective locations for technology demonstrator (outside of urban/suburban areas) and commercial (within urban/suburban areas) applications. To account for uncertainty in the temperature calculations Figure 10 shows mine shafts outside urban areas which exceed depths of 400 m bgl and 500 m bgl.

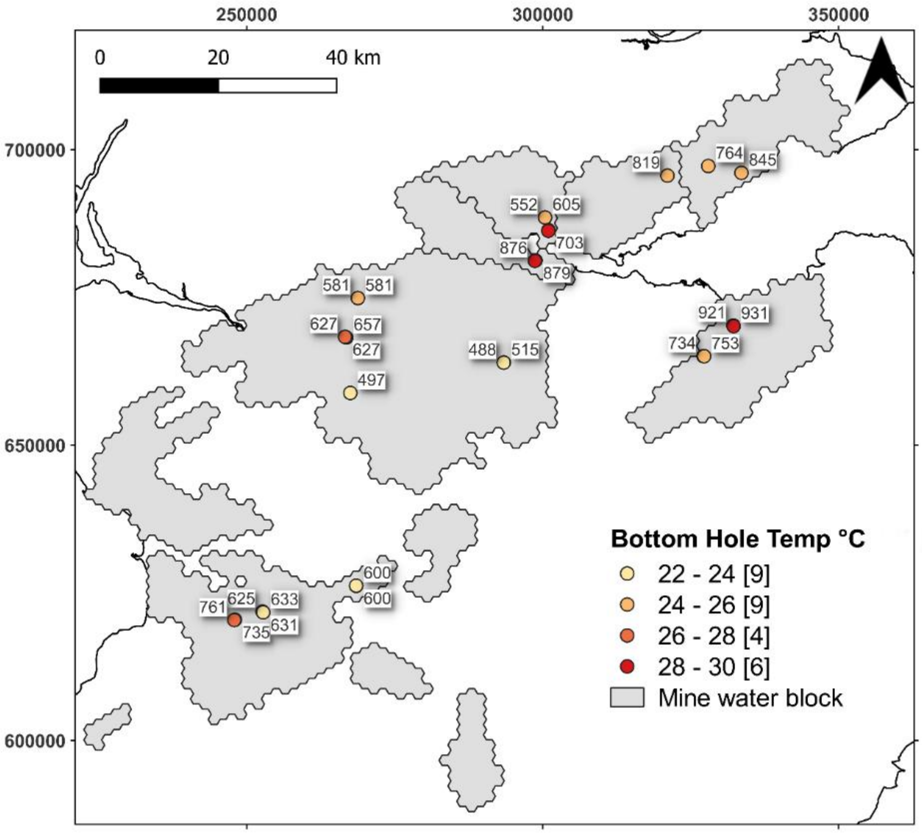

Figure 4.10: Shafts suitable for CO_2 loop technology. Location of shafts with expected equilibrium bottom hole temperatures of 22°C or greater. The number of shafts in each temperature range is given in brackets by the temperature legend. The numbers next to the shaft symbols on the map note the depth of the shaft (m bgl). Figure created by I. Otalega.

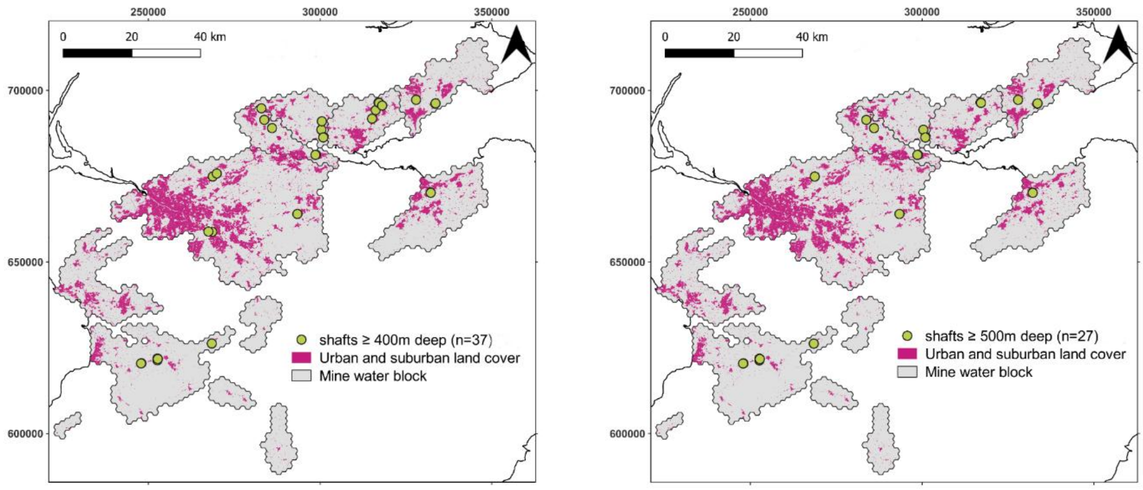

Figure 4.11: Comparison with urban and suburban land cover. Shafts that fall outside the urban and suburban land cover a) with depth ≥400 m bgl and b) with depth ≥500 m bgl. Figure created by I. Otalega.

4.3.3 Summary of screening results

Table 4.6 and Figure 4.12 show the number of mine shafts that met the screening criteria for each technology.

Table 4.6: Summary of the results of the screening process.

Technology	Heat extraction	TES (heat)	TES (electricity)	Gravity	UPHES	CAES	CO_2
Shaft characteristics considered	Depth >50m	Depth >50m bgl and volume >1000m^3		Diameter >3.5 m and depth >500m bgl	Depth >500m bgl and volume >1000m^3		Depth >100m bgl and temp >22°C
No. shafts - shaft screening only	2947 *Figure 4.4*	1035 *Figure 4.6a*		36 *Figure 4.8a*	19 *Figure 4.8b*		28 *Figure 4.10*
Total energy capacity (GWh)	**45.1 (ΔT = 10°C)**	**33.8 (ΔT = 10°C)**		**0.20**	**0.69**	**2.7**	**n/a**
Geographic factors considered	Within 1 km of heat source (EfW)		Within 1 km of primary substation				Outside sub/urban area
No. shafts - geographic screening	54 *Figure 4.5*	28 *Figure 4.6b*	288 *Figure 4.7*	8 *Figure 4.9*			27 *Figure 4.11*
Energy capacity (GWh)	**2.18**	**2.03**	**9.92**	**0.05**	**0.26**	**1.02**	**n/a**

Abbreviations: TES: Thermal Energy Storage, UPHES: Underground Pumped Hydroelectric Energy Storage, CAES: Compressed air energy storage, GWh: Gigawatt hours, EfW: Energy from Waste.

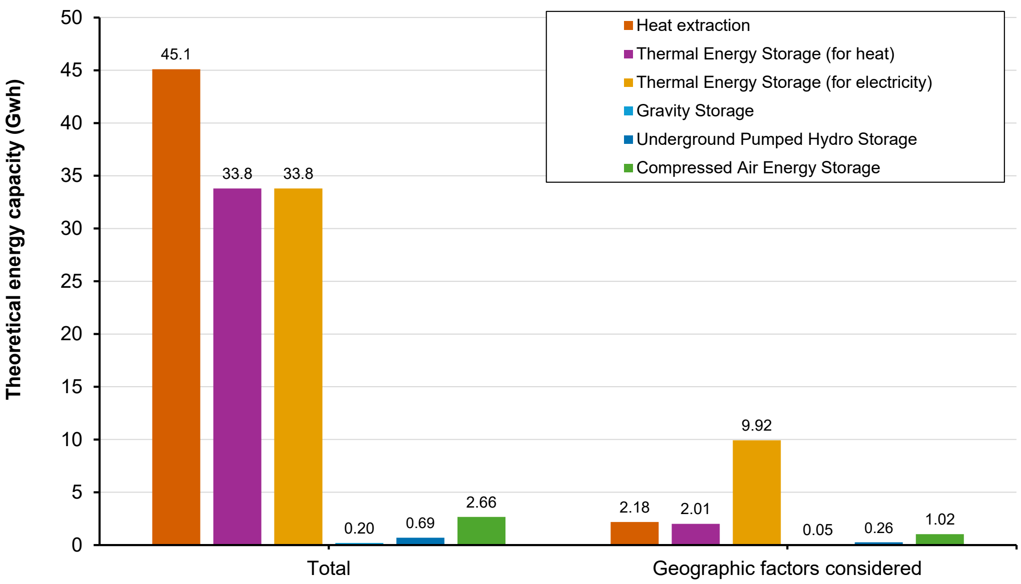

Figure 4.12: Summary of the theoretical energy capacities of six of the energy technologies considered in the screening process, based on the results of our screening process

4.4 Discussion

In this section, we will discuss the results of our screening process as well as the limitations of this method and the data used. There are several factors which would need to be considered on a case-by-case basis for each individual shaft if it were to be investigated for re-use for the different energy options. These have not been considered in this analysis as they are not available within the dataset and the purpose of this screening was to provide a high-level theoretical potential of the seven different energy technologies.

4.4.1 Discussion of the screening results

4.4.1.1 Heat provision and storage

The screening in this paper shows that the theoretical potential for re-utilising abandoned mine shafts is considerable should suitable technologies be identified to mitigate the risks. In order to meet net zero, the way that we generate electricity and heat our homes will have to decarbonise. The UK uses ~400 TWh for heating and cooling buildings (BEIS, 2018), only 8.4% of which was from renewable sources in 2022 (compared to 41.8% for electricity) (DESNZ, 2023). In Scotland 50% of the total energy consumption is used for heating, but only 3.9% (5,632 GWh) of this heat was generated from renewable sources in 2022 (Scottish Energy Statistics Hub, 2023). The mine shafts that meet the screening criteria for heat extraction could represent 45 GWh of resource, of which a sub-set are within 1km of an existing energy from waste plant, to offer a further 2GWh of recharge to 'top-up' the natural heat before reinjecting spent water (n.b. the 1km distance is an arbitrary distance. Heat networks can efficiently transport heat over larger distances, so this is a conservative screening criteria). This is only a small fraction of the total heat demand of Scotland (approx. 0.03%), however this amount is for the mine shafts only and does not include the wider mine workings, which represent a much larger void space. As the MRA only report a small number of potentially open shafts the above potential would rely on successfully trialling and demonstrating technologies that could utilise closed, capped, and/or collapsed shafts.

4.4.1.2 Electricity storage

ESO, the UK's electricity network operator, estimates that over 13GW of energy storage is required by 2030 and 40GW by 2050. Current technology options to make use of this otherwise curtailed electricity e.g. batteries, hydro, gravity, hydrogen, compressed air, etc., have limitations such as resource requirements, costs, scalability and market readiness. Wind curtailment payments in the UK almost doubled in 2020 to a total of £282M: enough to power 1.25 million homes and equivalent to £4 per MWh of wind energy generated (Staffel *et al.* 2020). As of 2020, there was 14GW pre-operational wind capacity in Scotland alone (Scottish Renewables, 2021), and curtailment payments will continue to increase as wind farms expand

and existing wind farms re-power with larger blades. A study by ESO and SSEN suggested curtailed wind could be reduced by up to 9% (540 GWh) in 2030 by incentivising electric residential heating and grid flexibility for which storage is the key (Myers *et al.* 2020). The technology with the highest potential energy storage capacity based on shaft characteristics and geographic factors was thermal storage using converted electricity, with a storage potential of 9.92 GWh across 288 shafts. The other storage technologies examined represent 1-2 orders of magnitude less storage but may be suitable options where shafts are 'dry' or only partially flooded. Many of the shafts meet the screening criteria for more than one technology. For instance, the 8 shafts which meet the criteria for CAES, UPHES and gravity storage are all the same. Further work is required to understand the optimal re-use of these shafts both from a technical standpoint, but also how they sit within the local energy system: for instance, proximity to alternative sources of waste heat or to large heat anchor loads.

4.4.2 Limitations of this study

The screening applied in the paper is based on simplistic assumptions about how these energy technologies can be applied, and on the data made available by MRA. Similarly, the estimates of the potential energy resource for each technology do not account for energy losses in a real engineered system. Partly this is because each shaft and energy system pair are so site-specific that more detailed screening is not appropriate. In addition, information such as the state of shaft abandonment and shaft water level was not available in the dataset used, as it must be requested on a site-by-site basis from The Mining Remediation Authority; such data is held in a range of formats and the labour required to manually interrogate the various MRA databases to extract the information makes it impractical to include the hundreds to thousands of shafts for which this data is available, in our high level screening. This section outlines possible considerations, as well as any data collection problems, which may additionally impact the implementation of these technologies.

For any of these sites, closer investigations of the Mining Remediation Authority archives, site or ground investigations may suggest that the site is unsuitable for a specific technology, cannot be developed without an unreasonable level of risk and therefore be deemed uneconomic. As such, these calculations show the maximum size of the opportunity.

4.4.2.1 Practical accessibility of shafts

Access to a shaft void space will vary on a case-by-case basis. Most shafts were capped or plugged and at least partially backfilled during colliery decommissioning. At some locations, access to the shaft void space was kept in place, or new access was created through an installed cap, for ongoing monitoring or to accommodate pumping infrastructure for required or potential water level management. Many older shafts have now had buildings, or other infrastructure, constructed over them and are completely inaccessible. Information on capping or plugging was not available within the mine entries database. Shaft completion information is often, though not always, available and must be requested from MRA on a case-by-case basis. For example, Barony No.3 Shaft has a 130 mm diameter borehole completed through a c. 33 m thick concrete plug which is used by MRA for water level monitoring, and Monktonhall No.2 Shaft is capped with steel girders and panels. The steel panels contain holes that afford shaft access points up to c. 30 cm in diameter and can be removed if appropriate safety measures are in place. In contrast the No. 1 and 2 Shafts at Comrie have no such access options (Whittington *et al.* 2023) and would therefore require additional drilling to get any form of novel technology into the shafts.

4.4.2.2 Shaft status

Mine shafts may be intact or have collapsed, and have been left unfilled, partially filled, or filled to the surface with gravel, concrete, or demolition rubble. Backfill status and materials are often unrecorded, although shafts abandoned since the 1980s will likely have been back-filled to at least just above the level of the shallowest roadways (NCB, 1982).A backfilled shaft may still be useful for heat extraction or thermal energy storage if the permeability of the infill material is high enough, but the engineering solution will differ for filled and unfilled shafts. The Mining Remediation Authority mine entries database indicates whether MRA holds information on shaft treatment by recording a true or false value in the treatment indicator field (Appendix 10.3). However, the database does not record what information is available and all information on shaft backfill or completion state needs to be accessed from MRA archives on a site-by-site basis. Similarly, the database does not contain information on how the shaft was constructed: if it was unlined, brick-lined, or concrete-lined. Information can also be found in shaft completion logs and sometimes on mine abandonment plans, both of which can be requested from MRA, if available. Some shaft completion, treatment, and abandonment details may also be found in documents held by mining museums and mining heritage groups.

4.4.2.3 Water level and composition

As soon as groundwater pumping stops, mine shafts began to refill, sometimes settling below the ground surface and sometimes draining at the surface. While it is common for shafts to take decades to fill (Malolepszy, 2003), refill rates are variable depending on local groundwater conditions and, where groundwater flow rates are very low, mine shafts have been known to remain unflooded for decades. As previously described, some of the technologies for which we are screening shaft suitability require the shaft to be empty, while others require the shaft to be flooded. Furthermore, assessing the composition of present shaft waters is critical for consideration of any potential scaling or corrosion risks on operational infrastructure (Walls *et* *al.*, 2021). Information on water level and chemistry can be acquired on a case-by-case basis from the MRA (though it is not available for all shafts). Qualitative information may also be found through local knowledge (Burnside *et al.* 2023). Future studies could consider screening of shafts based on existing water levels and mine water chemistry data, but this is likely to present a significant time-investment for the Mining Remediation Authority to make the data available on a regional or national scale. The online MRA Interactive Map viewer (MRA, 2024d) can show if a particular shaft is co-located with a MRA water quality monitoring point. Historic and ongoing water monitoring data can be applied for from MRA and, where available, may include single or time-series water level measurements, shaft temperature profiles (which in some cases can also include water conductivity), and water sample chemistry or vertical chemistry profiles. Even if a water monitoring point is proximal to the main shaft rather than within it, they can provide insight into shaft water level and water chemistry in the absence of direct data from shaft.

4.4.2.4 Ownership and permitting

Land ownership is an important factor in gaining access to a shaft location. The Mining Remediation Authority are responsible for subsurface shaft spaces and can own the land/ infrastructure immediately above the shaft (e.g. for locations that are regularly monitored). However, they might not own the land surrounding a shaft, so implementation may require separate access agreements with other landowners. The recent development of several UK mine water heating schemes (Jack *et al.* 2023) has allowed MRA to refine its permitting approach for more established mine water heat projects (e.g. Walls *et al.* 2021). If the site investigation stage involves ‘entering’ a mine (for instance, to sample water chemistry or gas), then a Mining Remediation Authority permit will be required. Minewater thermal projects will require a ‘minewater heat access agreement’ from the Mining Remediation Authority in order to extract heat from a shaft (GOV.UK, 2023). This may also require a groundwater abstraction licence from the appropriate environmental regulator, which in the case of this study is the Scottish Environmental Protection Agency (SEPA) (GOV.UK, 2023a). Any operation in a mineshaft must not make the environmental impact worse than those legacy impacts presently being managed by the Mining Remediation Authority and cannot impede the ability of the Mining Remediation Authority to manage the existing impacts. These impacts include movement of contaminated water and gas, and structural problems that could impact surface subsidence. Currently, the Mining Remediation Authority only have a process to grant access agreements for extraction of geothermal heat and for thermal storage concepts (www.gov.uk/government/publications/mine-water-heat-access-agreement). Substantial work is required to characterise a given site. Early engagement with the Mining Remediation Authority, other regulators and landowners is recommended to determine viable access to a shaft, appropriate permitting procedure, work required to feed into a permit, and indicative permitting timelines. Implementation of the more novel technological approaches in this paper requires further research into the likely risks and potential engineering mitigations.

4.4.2.5 Accidents and disasters

The nature of any mining disasters that affect a colliery might provide information relevant to a more detailed, health and safety-focussed screening process. For example, retrofitting of shafts from collieries with a history of explosive gas problems will have different operational and safety considerations to those where explosive gases are proven to not pose a problem. In addition to these operational issues, consideration needs to be given to the communities and families affected by historic accidents and disasters; some of these events happened within living memory, and relatives may still live nearby, causing sensitivities for potential shaft reuse. A list of accidents and disasters that occurred at Scottish collieries can be found online (Scottish Mining Website, 2018).

4.4.3 Reserves vs Resources

The concept of reserves and resources is commonly used in the mining and oil and gas industries (Kleppe and McKelvey, 1976, National Research Council, 2007, Moore and Friederich, 2021). Resource is a description of the total amount of a relevant commodity, which are either demonstrated or inferred (Wood *et al.* 1983). However, not all resources can be recovered. Recoverable reserves can be quantified into several categories. Technically recoverable reserves exclude resources that are, for instance, too deep to access using current technologies. As technologies improve, more resources may move into the technically recoverable reserve category (Wood *et al.* 1983; Boswell and Collett 2011). Economically recoverable reserves are those which can be recovered under current economic and regulatory conditions. The amount of economically recoverable reserves will vary as the commodity price and cost of extracting that commodity change (Boswell and Collett 2011). Wood *et al.* (1983) uses the concept of marginal reserves, which are potentially recoverable with a favourable change in economics. In recent years, many industries such as mining, have adopted the term ‘social licence to operate’ (Prno 2013; Moffat *et al.* 2016). This occurs when a development project has the “broad, ongoing approval and acceptance of society to conduct its activities” (Prno 2013) which is widely recognised as being a vital component to successful operations (Bice 2014). Economically recoverable resources which have a social licence to operate could be termed as ‘societally acceptable reserves’.

Here, we apply the concept of resource and reserves to the utilisation of abandoned mine shafts for energy extraction and storage. For heat extraction, the resource is the total heat in place: this can be calculated from the mine volume, water temperature, and heat recharge rate, if known. Technically recoverable heat reserves could include for instance, resources that are well connected, deep enough to be safely exploited, and have favourable water chemistry. Economically recoverable reserves could exclude sites that require expensive (deep) drilling to access, are too far from heat demand, or are situated close to a cheaper heat source.

For heat storage, on the other hand, the resource is the total available storage volume. Technically recoverable thermal storage reserves include shafts (and/or connected mine networks) that have acceptable water chemistry and can be exploited in a safe and environmentally responsible manner. Economically recoverable thermal storage reserves must have large enough volume or connectivity to minimise drilling or access costs, be close to heat supply and demand, not have a cheaper competing store nearby, and must be possible to meet environmental and safety regulations within a reasonable budget.

Figure 4.13 shows the concept of reserves and resources with the numbers from the screening analysis – at this early stage in the development of minewater thermal resources it is not possible to determine which are economically or technically recoverable reserves. Our screening criteria have identified the 'inferred resource' and 'inferred marginal reserves' (Wood *et al.*, 1983, CIM, 2014).

Given the lack of detailed information in the public domain, we asked the experts at the Mining Remediation Authority for their opinion on the number of accessible shafts in Scotland. They suggested, after consulting with their engineering and research teams, that there are only six shafts which they are currently aware of which are 'potentially suitable, open, or with access points'; however, to date, none of these shafts have been assessed, and their suitability for any such use is unknown. The MRA are also aware of another shaft that is open below a concrete plug close to a mine water treatment scheme, but that may not be suitable given its proximity to the MWTS. These seven shafts have been included in Figure 4.13. The MRA have not included the names or locations for any of these shafts. The MRA also listed three shafts related to MRA mine water treatment schemes and a further nine shafts which may be open which are related to drainage levels, but may be too shallow to repurpose for any of the energy technologies listed in this paper (n.b. MRA did not provide locations of open shafts to minimise any public safety risks). This list does not indicate that any of the shafts would be suitable, and all would need a full assessment. They included a caveat that there could be a number of other accessible shafts MRA are not aware of, but most likely these will be older, meaning they are more likely to be shallow and to have less structural integrity, and that they have not conducted detailed studies of all the remaining shafts in the database.

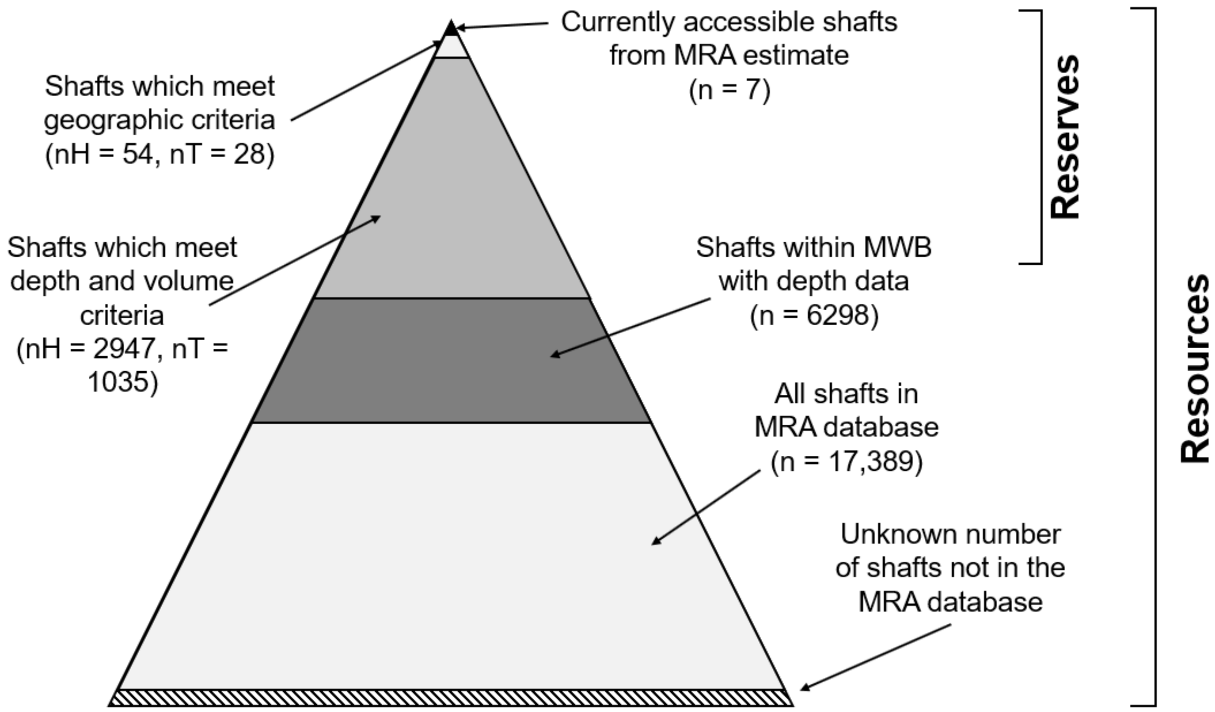

Figure 4.13: Estimates of resource (n) and reserves for heat extraction (nH) and thermal storage (nT) in Scottish mine shafts (n.b. triangles are scaled to the number of nH shafts).

As is commonly seen in the hydrocarbon and mining industries, technological development could move mine shaft resources into reserves, and marginal reserves into economically viable reserves. Improvements in site characterisation and ground investigation technologies could reduce appraisal costs at mine sites. A greater understanding of risk within mine shaft systems will drive down capital costs of appraisal, installation and operation. Novel technologies could be developed to take advantage of shafts that have been capped or plugged, or which have been partially or fully backfilled. Novel technologies could also be developed that isolate mineshafts from wider mine workings, which will be essential for compressed air storage. We therefore present the full inventory of Scottish shafts in this paper, not because all of these are useable now, but rather as an estimate of the size of the resource as an incentive to drive such technological development.

4.5 Conclusions

This study provides a high-level screening of all recorded mine shafts in the Scottish coalfields for the installation of novel technologies to generate low-carbon renewable electricity, heating and cooling, and to provide energy storage. The analysis is based on GIS data from the Mining Remediation Authority (MRA) on shaft location and depth, as well as geothermal gradients calculated for each mine water block (MWB) in the Scottish coalfields by Farr *et al.* (2021). The MRA data contained 17,896 mine entries (shafts), of which 6,298 contained shaft depth information. Screening criteria have been defined for a range of novel energy technologies, but do not consider detailed engineering options, which will be highly site-specific. Note that the Mining Remediation Authority mine entries dataset contains every mine shaft that the Mining Remediation Authority have ever recorded. The file does not include information on how many of those shafts are accessible or open, or details on the state of the shaft: all information that would be required to evaluate if a given shaft could be suitable for energy technology reuse, and which may be available in the MRA archives.

Based on our simple depth and volume screening criteria, over 2,900 shafts meet the criteria for heat extraction, 1,035 meet the criteria for thermal energy storage and tens of shafts meet the criteria for potential energy storage (gravity storage, underground pumped storage, compressed air energy storage, and CO_2 loop power generation). When considerations of local geographical screening criteria are applied, such as the need to be close to heat-customers for utilisation of heat, the total number of shafts drops to 54 for heat extraction and 288 for thermal energy storage. This only accounts for domestic heat customers and does not include large rural heat customers. For CO_2 loop technology, we looked at shafts which were situated away from urban and semi-urban areas, as this is an experimental technology: 27 shafts meet the criteria for this technology.

Additional information on shaft completion, backfill status, and whether a shaft was flooded or dry can only be requested from the MRA archives on a case-by-case basis and, therefore, could not be included at this high-level screening stage. It should be noted that the amount and detail of shaft-specific information available in the MRA archives varies from site to site. Additional site-specific factors that should be considered include sensitivities over any historic site accidents, present and historic water level, mine water composition, practical accessibility to the shaft void space, subsurface and surrounding land ownership, and permitting requirements. Even with this information, MRA currently permit only heat extraction and storage within mine workings.

Given the limited data available in the shaft entry database and recognition of the low number of currently accessible shafts, our estimates should be considered to be the potential theoretical resource. Information from the MRA suggested they had records of just 19 shafts that were potentially accessible, with only 6 of these worthy of consideration for any geo-energy use: these represent current reserves. Further work to demonstrate the feasibility and safety of repurposing abandoned mine shafts for any or all of these technologies is required. However, this study shows that the opportunity for deploying such novel technologies is considerable. Even if risk-mitigating technologies can be developed and proven, moving a given shaft from resource to reserve will also require site-specific desk studies and shaft and site characterisation. The magnitude of the opportunity presented in this paper should provide motivation to develop novel technologies for accessing shafts, isolating them from wider mine workings and effective mine shaft site characterisation approaches to move from potential resource to a ready-to-be-realised reserve for a net-zero energy future.

Data Access

Legacy mining data used in this study from The Mining Remediation Authority were obtained under a Non-Commercial Use License. Shaft location data used in figures was reproduced with the permission of © The Mining Remediation Authority (all rights reserved). This information can be requested via application to their data solutions team via https://www.gov.uk/government/publications/apply-to-use-coal-authority-data. Mine Water Block temperature information is available as an open-access GIS shapefile from the Data.gov.uk "Temperature Maps of the British Coalfields" webpage. The UK Centre for Ecology & Hydrology (UKCEH) Land Cover Map 2020 was accessed via the EDINA operated Digimap service. Access is free for registered individuals from subscribed higher and further education institutions in the UK.

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5. CHAPTER 5: Testing the reliability of volume estimation methods for underground coal mine workings

5.1 Introduction

For both thermal energy storage and heat extraction, volume is a key parameter for estimating either the storage capacity or the 'heat in place' available from the water within the void (Chapter 4.2). The size of the potential for using mine shafts for various energy solutions was estimated in Chapter 4, but mine shafts were not the only voids created by mining activities. Vast underground networks of voids were left by the extensive mining that took place across Scotland. Unlike mine shaft volumes, the volume of underground workings is harder to estimate, due to their increased spatial complexity, and a quick, simple, and reliable method of estimating their volume has not been established. There are several high-level estimates of the potential heat resource or storage capacity of mine workings in Scotland or the UK (Gillespie *et al.*, 2013; Adams and Gluyas, 2017; Todd *et al.*, 2019), but they each rely on numerous assumptions that introduce uncertainties (discussed further in Section 7.1). This chapter describes procedures that aimed to test methods of estimating of mine volume based on available historical and spatial data, both for individual collieries and for Scotland as a whole. Moreover, it will highlight the risks and limitations of using these volume estimation approaches. This chapter will draw on findings from the literature review in Chapter 2 especially Section 2.3 on thermal storage, and Section 2.4.2 on the history of coal mining in Scotland.

A quick and reliable method, based on readily available data, for estimating volume of mine workings would be useful at both an individual colliery level, and a national level. Understanding the total mine void volume may help to unlock investment in minewater heating or storage technology, if the potential resource[9] is large enough to contribute to wider decarbonisation efforts in Scotland. It could also help to rule out utilisation of mine water energy in certain areas and so avoid wasting any further time investigating it. For developers and landowners, estimating the volume of individual mines would be useful when they are considering whether to investigate an area for mine water thermal energy with a ground investigation. If the estimates are not economical enough to provide sufficient heat or storage,

[9] As introduced in Chapter 4, the concept of resource and reserve comes into play here. These methods estimate the 'total potential resource', not all of which will go onto become 'proven accessible reserves' which could be exploited for heat extraction or storage.

then a developer can consider alternatives for heat provision or thermal storage on their site and not waste money on expensive drilling campaigns.

Three methods of quantifying underground mine void volume are explored in this chapter. The first method uses the shapefiles produced by The Mining Remediation Authority (formerly The Coal Authority) after their archive was digitised in 2011, and the seam thicknesses provided in that dataset (Method 1, MRA, 2023c). The second method uses individual digitisations of abandonment plans to calculate the area of the workings and the seam thickness given on the plans to estimate volume (Method 2). One colliery, Seaforth, has been digitised by the author and the remaining three are from existing digitisations (Andrews and Shipton, 2021, Otalega *et al.*, 2022). Thirdly, historical coal output data (mass of coal in tons) and the density of coal are used to calculate the volume of coal mined out as a proxy for the void left by mining activities (Method 3).

5.2 Collieries used in this study

The four collieries are Cardowan Colliery in North Lanarkshire, and Seaforth Colliery, Killoch Colliery, and Barony Colliery, in East Ayrshire (Figure 5.1). These collieries were chosen based on the availability of individually digitised abandonment plans and access to original abandonment plans. This section describes the location, geological setting, and historical context for each of the four collieries, starting with Seaforth Colliery as the abandonment plan for this colliery was digitised by the author, followed by Cardowan Colliery, digitised by Andrews and Shipton (2021), and Barony Colliery and Killoch colliery both digitised by Otalega *et al.*, (2022).

These four collieries represent a range of ages and mining methods which help to constrain how the structure of the underground voids may affect volume estimates. The two main types of mining are pillar and room (aka stoop and room) and longwall mining. The age of the target workings is important, as older workings may have different characteristics compared to those worked using more advanced methods (Andrews *et al.*, 2020). Pillar and room mining is an older method of mining and involves leaving pillars of coal behind to support the roof. Longwall mining is when a wall of coal is mined as a single slice until the end of the panel is reached, the roof above collapses and leaves behind a deposit known as goaf (Thin *et al.,* 1993).

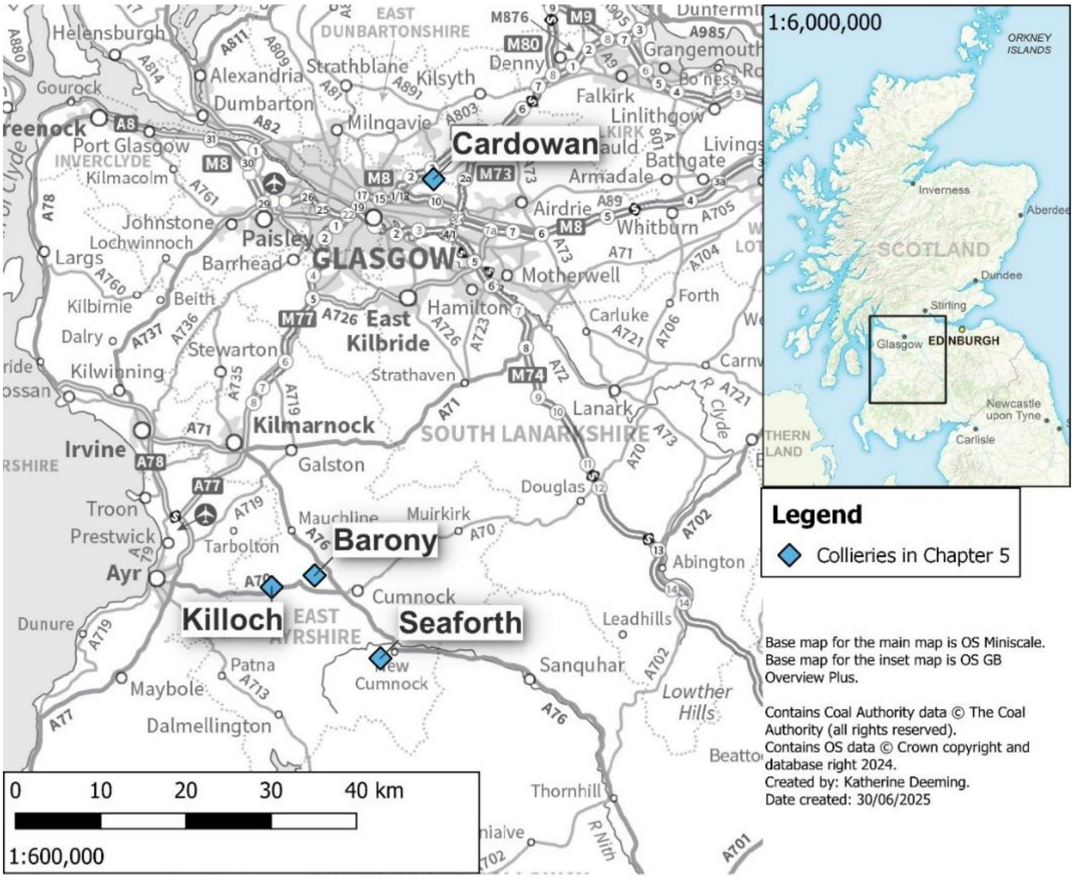

Figure 5.1: Locations of the four collieries used in this study. Map created by KD in QGIS. Contains data from MRA (2022) and Ordnance Survey (2014 and 2024b).

5.2.1 Seaforth Colliery, East Ayrshire

Seaforth Colliery is approx. 2.7 km south-west of the village of New Cumnock in East Ayrshire. Production lasted for 13 years from 1940 to 1953, and the colliery was abandoned in 1955 (Oglethorpe, 2006). The bedrock at Seaforth Colliery is that of the Scottish Middle Coal Measures Formation (BGS Geoindex, 2025) and seven coal seams, known as Five Feet, Eight Feet, Three Feet, Four Feet, Diamond, Musselband, and Blackband, were mined. The two shafts were surface mines (see Section 5.5.1.1) driven at angles of 1 in 3 and 1 in 5 (Oglethorpe, 2006). Both longwall and stoop and room mining methods were used to access the coal face (Oglethorpe, 2006).

Records and information on Seaforth Colliery are limited with no named record of Seaforth Colliery on the historical mapping available on Edina Digimap (2023). The (presumed) colliery building which is shown on the abandonment plans (2 of 7) is illustrated on the 1960s map, just to the south of Bank House. There is also evidence of this building on a 1946 aerial photograph (NLS, 1946). Seaforth Colliery was sunk by New Cumnock Collieries Ltd in 1936 on the land of the Knockshinnoch colliery, which was established in 1870s, and around 700 m northeast of Seaforth Colliery (Historic Digimap, 2025b, New Cumnock History, n.d.). The name 'Seaforth' was brought to New Cumnock by Kenneth McKenzie who moved to the parish in the 1850s to go into business with John Hyslop in 1860 when they set up the Bank Coal Company (New Cumnock History, 2014). The name Seaforth derives from the sea loch between Lewis and Harris in the Outer Hebrides (Gaelic: *Loch Shiphoirt)* (New Cumnock History, 2014). In 1948, there were 125 employees at Seaforth Colliery and there was a daily coal output of 200 tons, and an annual output of 58,000 tons. There were no pithead baths or canteen, and the coal was washed at Knockshinnoch Castle Colliery (Oglethorpe, 2006), indicating the small size of this colliery. In the present day there is no evidence of Seaforth Colliery on the surface, and the area appears to be used for forestry (Digimap, 2025b).

5.2.2 Cardowan Colliery, North Lanarkshire

Cardowan Colliery was located on the eastern outskirts of Glasgow, just south of the town of Stepps (Oglethorpe, 2006). A village called Cardowan was built up around the former brick works and colliery, which was operational for 54 years from 1929 to 1983 (Oglethorpe, 2006; Seven Lochs' Memories, 2022). The bedrock at Cardowan colliery is made up of Carboniferous sedimentary rocks; the Lower Limestone Formation, Limestone Coal Formation, Upper Limestone Formation and Scottish Coal Measures Group (Andrews and Shipton, 2021, BGS Geoindex, 2025). Four coal seams, namely Meiklehill Main, Kilsyth Coking Meiklehill Wee, and Cloven were mined at Cardowan using longwall mining. Seam thickness ranged from 0.6 to 1.0 m and were found at a depth range of approximately 400 metres below ground level (m bgl) to 628 m bgl (Andrews and Shipton, 2021)

Prior to the colliery, there was a fireclay brick works at Cardowan from the 1850s until 1902, with a village of workers built up around it (Seven Lochs' Memories, 2022). Cardowan Colliery started production in 1929, with two shafts sunk in 1924 and 1928, both 626 m deep (Andrews and Shipton, 2021, North Lanarkshire Council, n.d.). The initial workforce of the colliery was around 800 men and by the mid-1930s the colliery employed around 1000 men (Seven Lochs' Memories, 2022, North Lanarkshire Council, n.d.). At the time of nationalisation, the coal output at Cardowan was 418,500 tons per year (Oglethorpe, 2006) and the coal was used to fuel trains and domestic fires in the local area (North Lanarkshire Council, n.d.).

The colliery was expanded by the National Coal Board (NCB) in the 1950s with a third shaft sunk in 1958 to increase production. This expansion saw locomotion installed underground, and the main roadways were reinforced and widened (Andrews and Shipton, 2021). The third shaft had a 23-metre-high steel-framed tower which housed an electric winder, whereas the two older shafts were powered by steam winders (Figure 5.2; Scottish Cave and Mine

Database, 2025a). Employment reached a peak in 1959 when there were 1,970 people working at the colliery (Oglethorpe, 2006, North Lanarkshire Council, n.d.). During this time, the colliery reached a peak output of 2,750 tons per day and now supplied coal to the Clyde Iron Works and the new Ravenscraig steelworks (Seven Lochs' Memories, 2022).

The coal seams at Cardowan were known for being very gassy, causing explosions in the mine in 1932, which killed 11 men (Scottish Mining Website, 2018, NMRS, n.d.), in 1960, which killed 3 men (Scottish Mining Website, 2014), and in 1982, which badly injured 40 men but caused no fatalities (Allister and Hamilton, 1983). In the 1960s, the methane from the pit started to be drained from the coal seams and used as fuel for the colliery boilers, as well as a new whisky bottling plant in Stepps (Seven Lochs' Memories, 2022; Historic Environment Scotland, 2025). Cardowan was the last deep mine in Lanarkshire when it closed in August 1983 (Scottish Cave and Mine Database, 2025a). After closure, the colliery site was cleared and redeveloped as a residential area, the shafts were treated and are now covered by a playground (Andrews and Shipton, 2021; Scottish Cave and Mine Database, 2025a).

Figure 5.2: Headgear of one of the two original shafts at Cardowan Colliery, 1966 (Hume, 1966).

5.2.3 Barony Colliery, East Ayrshire

Barony Colliery was located in East Ayrshire, 2 km west of Auchinleck, and 4 km northwest of the town of Cumnock and the colliery operated from 1910 to 1989 (Oglethorpe, 2006) and over its lifetime, four shafts were sunk at the colliery. The bedrock beneath Barony Colliery is that of the Scottish Coal Measures Group, made up of sandstones, siltstones, mudstones, and coal seams (Otalega *et al.* 2022, BGS Geoindex, 2025). Nine coal seams, namely, Ell, Main, Major, Ayr Hard, 40 fathom, 36 fathom, Musselband, 20 fathom, and 17 fathom, were mined at Barony with a depth range from around 150 to 650 m bgl (Otalega *et al.*, 2022). The layout of the underground workings at Barony Colliery are both laterally and vertically complex which reflects the long history of the mine and the changing mining methods over its lifetime (Otalega *et al.* 2022).

By the beginning of the 20th Century, most of the coalfields of North Ayrshire had been exhausted and coalfields in East Ayrshire began to be developed (Barony A Frame Trust, 2012a). Two shafts were originally sunk in the early twentieth century and production started in 1910 (Oglethorpe, 2006). During the 1930s, the colliery was reconstructed and modernised and included the building of pithead baths in 1932 and the sinking of a third shaft which began in 1938. The aim of adding a third shaft was to increase the daily output of the mine from 1500 tons to 2500 tons per day and to improve ventilation. The development of the colliery was delayed by the outbreak of the second world war and was completed after nationalisation by the National Coal Board in 1949. When the third shaft was completed, at 635 metres deep it was the deepest mine shaft in Scotland. The A-frame was completed in 1954 and held two sets of winding gear (Figure 5.3). It is one of only two of that frame type ever constructed and the only one still standing (Barony A Frame Trust, 2012a).

In 1949, Barony was considered by the NCB as a “major commuter pit” which could take on miners from surrounding collieries that were closing (Perchard, 2020). At the time of nationalisation there were 15 collieries in the vicinity of Barony colliery, but twenty years later over half of them had closed (Perchard, 2020). In 1955, Barony was among the collieries chosen for modernisation the NCB’s ‘Scotland’s Coal Plan’ (Oglethorpe, 2021). Barony Power station, constructed by South of Scotland Electricity Board, opened in 1953 and burnt coal slurry from the colliery washery. Barony was one of only two collieries in Scotland to have a power station adjacent to it (University of Wolverhampton, n.d.). The power station was closed (Barony A Frame Trust, 2012b) and demolished in 1982 (see Figure 5.4).

On the 8th November 1962, tragedy struck Barony Colliery, the No.2 shaft collapsed (Figure 5.5) causing four men to be entombed in the mine (Thomas Fyvie and George Wade, both contractors; Henry Green, oversman; and John McNeil, deputy; Perchard, 2020, University of Wolverhampton, n.d.). A week later, on the 14th November, the head stocks fell into the shaft and as a result the bodies of the miners who were killed were never recovered (Barony A Frame Trust, 2012b). After this disaster, the colliery was closed and 1100 of the 1600 workers were laid off, 300 were retained to clear up the colliery site, and work was found for the remaining 200 men at other pits. Shafts No.1 and No.2 were filled in leaving only shaft No.3 which then made it illegal for Barony to operate with just one shaft as there was no escape shaft (Barony A Frame Trust, 2012b). After a period of uncertainty, in 1965 a fourth shaft was sunk at Barony to provide ventilation and emergency access (Oglethorpe, 2006). This was during a period of colliery closures across Scotland with 60,000 jobs lost between 1947 and 1969 (Perchard, 2020). Barony Colliery was saved through a community campaign carried out by the NUM, town councillors, churches, and the local trades council as well as political intervention from the local MP (Perchard, 2020). Additionally, construction of Longannet coal-fired power station in Fife began in 1965 (Power Stations of the UK, 2025) and this may have ensured the need for the coal from Barony (Barony A Frame Trust, 2012b) and coal production restarted in 1966.

Barony Colliery faced problems with understaffing and geological difficulties during the 1970s and 1980s which had an impact on the output of the colliery (Coal and Community, n.d.). Colliery closures during the 1980s meant that Barony was left as the only colliery outside of the Forth Valley (Scottish Cave and Mine Database, 2025b) and the colliery eventually closed in 1989 after 79 years of operation (Oglethorpe, 2006, Barony A Frame Trust, 2012c). At the time of closure there was a workforce of 400 (Perchard, 2020).

Figure 5.3: The Barony A-frame. Picture taken by K.B. Deeming, September 2024.

Figure 5.4: Barony Power Station on the day it was demolished in 1982. Images from ayrshirehistory.com (Tannock, 1982).

Figure 5.5: The Barony No.2 shaft its collapse in November 1962. Image from Perchard, 2020.

5.2.4 Killoch Colliery, East Ayrshire

Killoch Colliery was approximately 3 km to the west of the village of Ochiltree, and about 4km northeast of the village of Drongan in East Ayrshire. Killoch is approximately 5km to the west of Barony Colliery, and both are in the Mauchline Basin, a sub-basin of the Midland Valley (Otalega *et al.*, 2022). Development of Killoch Colliery was started by the NCB in 1953 and was part of the 'super-pits' developed by the NCB post-nationalisation (The Gazetteer for Scotland, 2021). In 1960, coal production began from three seams, the Main Coal, Ell Coal, and Ayr Hard (Oglethorpe, 2006, Otalega *et al.*, 2022). In the mid-1970s, the workings of the Main seam at Killoch were connected to the Barony workings to provide additional ventilation (Otalega *et al.*, 2022). Unlike Barony, the network of underground workings at Killoch are a well organised network of arterial roadways leading to individual panels (Otalega *et al.*, 2022), reflecting the newer nature of Killoch, meaning that it could be planned from the beginning of production, whereas Barony's workings grew over time. These roadways were large and could be over seven metres wide, and five metres high (Future Museum, 2025b) the large scale of these modern roadways is demonstrated in Figure 5.6. However, the intended scale of the underground working was never realised (Otalega *et al.*, 2022). The concrete structures which formed the winding towers were designed by Egon Riss, and Austrian architect who became the Chief Production Architect for the NCB's Scotland division and designed many colliery buildings in Scotland (The Gazetteer for Scotland, 2021, Arthur, 2022).

Notably, Killoch was the first colliery in Scotland to reach an annual output of one million tons in 1965 (Oglethorpe, 2006). At that time Killoch employed 2300 workers (The Gazetteer for Scotland, 2021). Coal mined at Killoch was generally exported to Northern Ireland for power stations (The Gazetteer for Scotland, 2021). Killoch closed in 1987, and the two shafts were reportedly left open and capped with concrete (Otalega *et al.*, 2022).

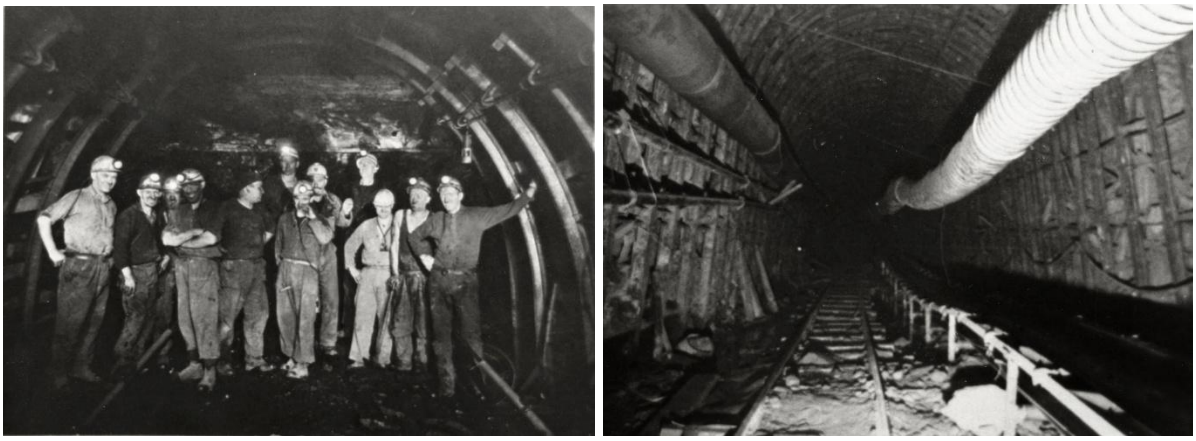

Figure 5.6: Left: A tunnelling crew and safety officials at Killoch Colliery (Future Museum, 2025a). Right: A roadway at Killoch Colliery with ventilation ducting. This roadway is 7.62m wide and 5.59m high (Future Museum, 2025b).

5.3 Methodology

The three methods for estimating volume of abandoned mines investigated in this study are as follows:

- Method 1 – Large-scale digitisation: Estimating volume using Mining Remediation Authority shapefiles and seam thickness data (MRA, 2023c)
- Method 2 – Individual digitisation: Estimating volume of mine workings by digitising historical mine plans using QGIS
- Method 3 – Historical coal output data: Calculating the volume of underground mine workings using coal output data (Oglethorpe, 2006) and coal density

In order to compare the three methods, each method has been used to calculate a volume of mine workings for four collieries described in Section 2. This volume does not include mine shafts, only underground workings[10]. Abandonment plans for Seaforth Colliery (MRA, 2023d) were digitised on QGIS by the author and the digitisations and estimated volumes of the other three are from Andrews and Shipton, 2021 (Cardowan) and Otalega *et al.* 2022 (Barony and Killoch). All three of these methods assume that all the mine workings are all still complete voids, which will give an overestimate of the true volume because mine workings will have collapsed since they were abandoned. However, the collapsed material, known as goaf, may still be useful for thermal storage as it can be highly permeable and/or porous (Younger and Robins, 2002) Information on how each of the methods were carried out and assumptions made for each method will be discussed below.

Coal mine abandonment plans are the primary source of data for Methods 1 and 2. When coal mines were closed or abandoned, mine abandonment plans were produced to make a record of the extent of coal extraction at each colliery, the point of entry into the mine, and how the mine related to features on the surface (Figure 5.7). Abandonment plans also sometimes included cross sections with the name and thickness of the coal seam mined out at that location, usually in feet and inches (Figure 5.8). Abandonment plans must be requested from The Mining Remediation Authority archive in Mansfield for individual collieries (MRA, 2025).

[10] The estimates from the literature (Gillespie *et al*., 2013, Adams and Gluyas, 2017, and Todd *et al*., 2019) also only considered underground workings and did not include mine shaft volume.

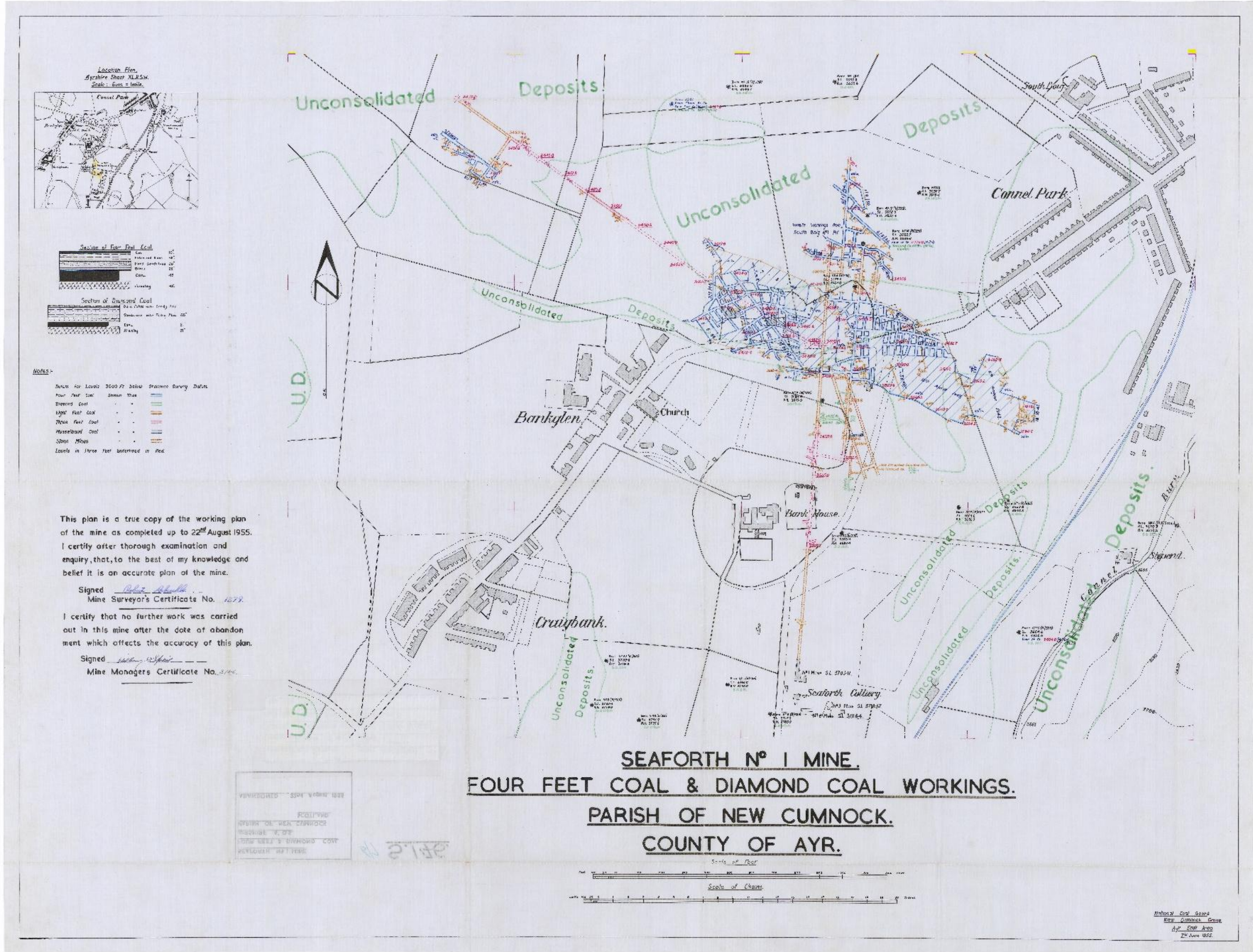

Figure 5.7: Example of an abandonment plan from Seaforth Colliery, plan 5 of 7. Received by K. Deeming from The Coal Authority on 6th November 2023 (MRA, 2023d).

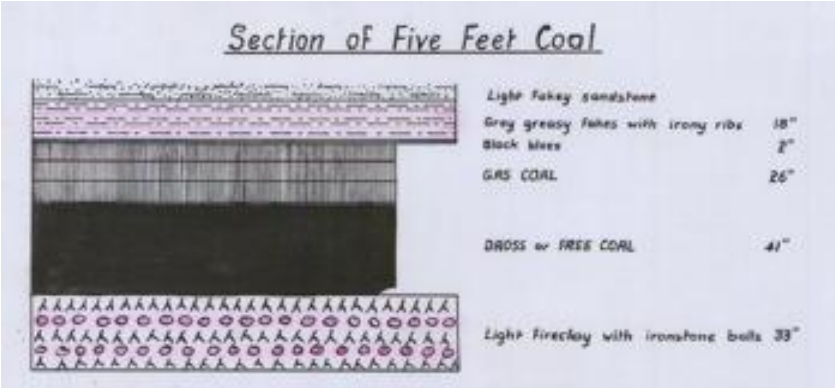

Figure 5.8: Extract of the Seaforth Colliery abandonment plan for the Five Feet Coal Workings showing the strata surrounding two coal seams (gas coal and free coal) and the thicknesses of each (in inches). Extract from Seaforth Colliery abandonment plans (1 of 7) showing the Five Feet Coal Workings. Received by K. Deeming from The Coal Authority on 6th November 2023 (MRA, 2023d).

5.3.1 Method 1: Large-scale digitisation

There are around 120,000 coal mine abandonment plans held by the Mining Remediation Authority in their Mansfield archive which were digitised to form the primary source of the underground workings dataset (MRA, 2015) The shapefiles are polygons showing the area of mined-out panels and associated data, (data fields listed in Appendix 10.4). The data can be downloaded from Edina Digimap as GIS shapefiles (MRA, 2023c, EDINA Digimap, 2025a).

For this study, the data for the Central Belt of Scotland was used and it contains 33,892 polygons (Table 5.1) representing panels of coal mine workings (31,201 polygons, 92.1%). It also includes other minerals such as ironstone (3.0%) or oil shale (4.2%, Table 5.1**:** and Figure 5.9). Less than 1% of the database is made up of other minerals such as fireclay and limestone (Table 5.1**:**). 98% of the polygons in this dataset (33,514) have a value for seam thickness, and the majority had thicknesses of between 60 and 100 cm (Figure 5.10).

The ‘Add geometry attributes’ function was used to add an area (in m^2) to each panel polygon, which was multiplied by the seam thickness of each individual panel. This gives an estimate of volume (in m^3) for each mined-out panel in the dataset. To separate individual collieries from the larger dataset, the ‘extract by attribute’ was used on QGIS to extract the panels for each colliery based on the ‘colliery name’ data field. The panel volume estimates for each colliery were summed to give the estimated total volume of the mine. This method does not include areas of the mine which were mined but were not coal (i.e. waste rock), because it only records panels (MRA, 2015), but these areas would still be a void.

5.3.1.1 Assumptions for Method 1

This method assumes that the MRA shapefiles are an accurate and reliable digitisation of the original abandonment plans and that the polygons provided are complete both for each colliery, as in they show all parts of the mine, and for Scotland, as in no collieries have been left out, and that there are no repeated panels or collieries. It also assumes that the original abandonment plans were a true record of the underground void spaces for each colliery, and that the seam thicknesses provided were a good representation for each colliery. In reality, seam thickness can be highly spatially variable even within a single mine (Andrews *et al.,* 2020).

Table 5.1: Summary of the Mining Remediation Authority underground workings dataset for Scotland, sorted by the type of mineral being mined. Coal is highlighted in bold. The areas of coal, oil shale and ironstone mining are shown in Figure 5.9. MRA (2023c) data downloaded from EDINA Digimap on 30th November 2023. The total volume is calculated from the sum of the volume of each individual panel.

Mineral	Polygon count	Percentage of total polygons	Estimated total area (m^2)	Estimated total volume (m^3)
Coal	**31,201**	**92.1%**	**2,965,036,170**	**3,528,707,463**
Oil Shale	1422	4.2%	68,695,264	145,240,520
Ironstone	1022	3.0%	83,081,452	72,568,436
Fireclay[11]	123	0.4%	10,037,782	21,335,433
Limestone	121	0.4%	6,057,429	11,531,688
Flagrock	1	0.003%	301,363	229,036
Ganister[12]	1	0.003%	15,985	15,985
Copper	1	0.003%	545,086	637,750
Total	**33,892**	**100%**	**3,133,770,529**	**3,780,266,310**

[11] Silicate of aluminum oxide used in brick making (Barrowman, 1886).
[12] Ganister is a highly siliceous fine-grained sandstone (Percival, 1983)

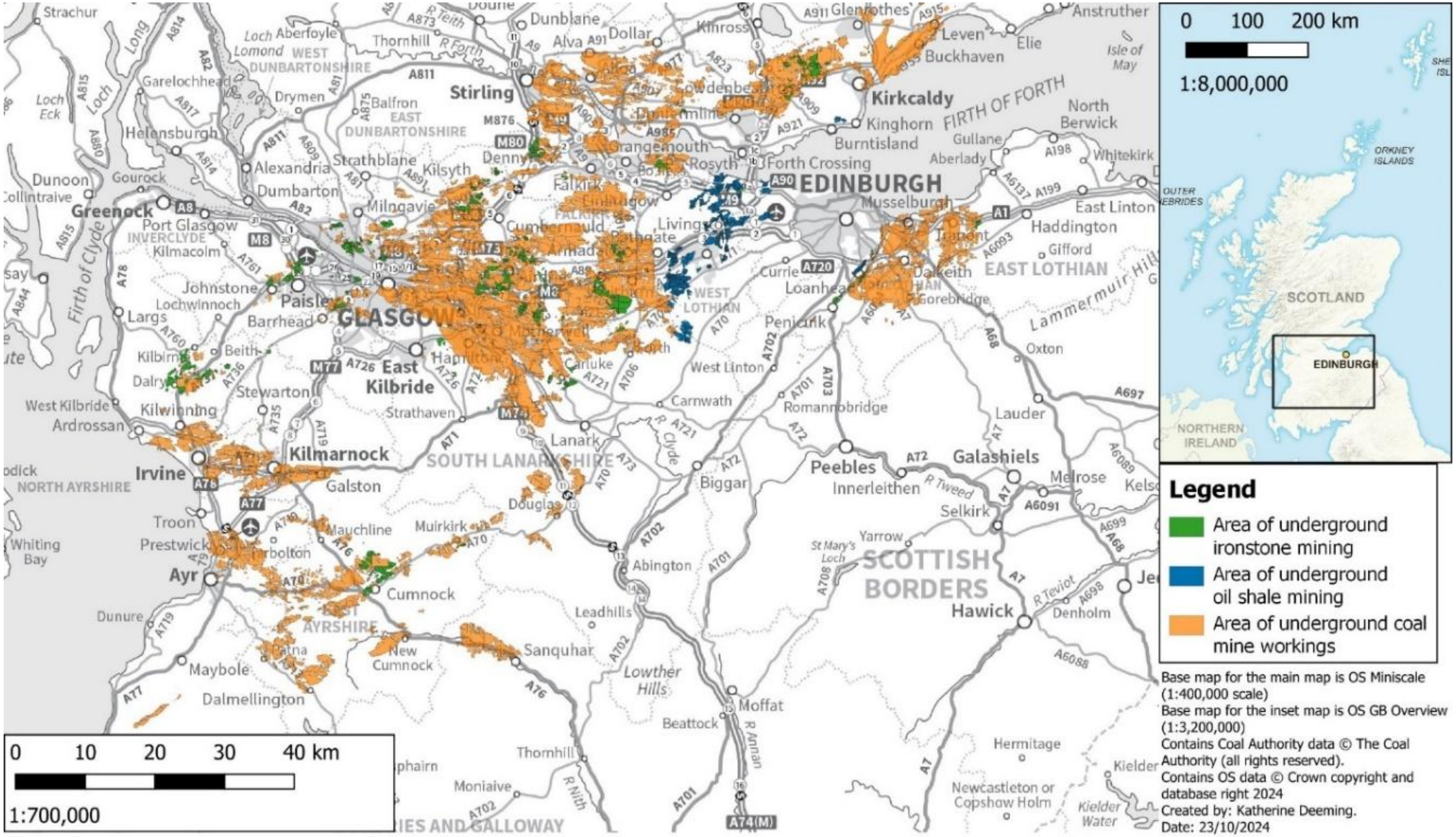

Figure 5.9: Areas of ironstone, oil shale, and coal mining in the Central Belt of Scotland included in the MRA database. For this study only areas of underground coal mining were used in the volume analysis. Created by KD on QGIS. Contains data from MRA (2023c) and Ordnance Survey (2014, 2024b).

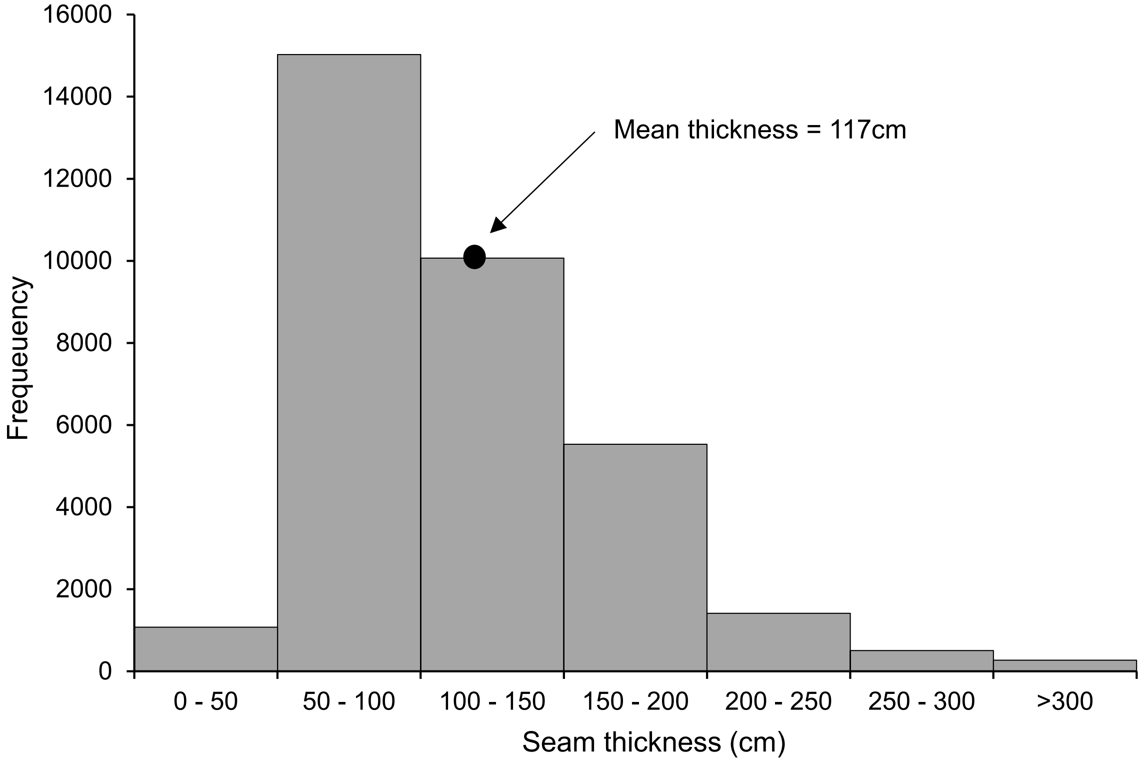

Figure 5.10: Histogram of seam thicknesses of the underground workings (for all minerals) in Scotland. N = 33,892. Mean = 117 cm. Contains data from MRA (2023c).

5.3.2 Method 2: Individual digitisation of abandonment plans

The polygons in Method 1 include areas of unmined coal: for instance, a pillar and room working will be represented as a single polygon even though the pillars were not mined. To address this, abandonment plans can be individually georeferenced and digitised in QGIS to calculate a surface area. The volume of each seam that was potentially mined can be calculated by multiplying the mined-out area by the coal seam thickness (Figure 5.8). The total void volume of the mine includes areas of the mine which were mined out but were not coal (known as stone mines[13]), as rock will have been removed to reach the coal seams (for example if there was a small band of rock between coal seams it will have been removed with the coal).

Seven abandonment plans from Seaforth Colliery near New Cumnock in East Ayrshire were obtained from the Mining Remediation Authority in November 2023 following a visit to their archives in Mansfield. Each plan showed one of the seven different levels of mine workings in

[13] "*A mine driven in barren strata*" (Barrowman, 1886).

Seaforth Colliery. The abandonment plans were georeferenced in QGIS using surface features on the georeferenced historical maps, such as buildings, from the 1860s and 1890s (Edina Digimap, 2023).

Seaforth Colliery had areas of pillar and room mining and longwall mining (Figure 5.7). Longwall mining is shown on the plans with hatched diagonal lines. To calculate the area (in m^2) of the mine in QGIS, one large polygon was drawn around the outside of the worked coal seams using the ‘create layer’ tool, to represent the void space or ‘rooms’ shown in yellow on Figure 5.11A. Smaller polygons were drawn around the pillars left behind, shown in brown on Figure 5.11A. Once all the pillars were assigned a polygon that layer was subtracted from the yellow polygon using the ‘Difference’ function to leave the areas of void space (Figure 5.11A). If needed, polygons were also added for areas marked as being stone mines (Figure 5.11B). Once complete, the area in square metres was added to the yellow polygon using the ‘Add geometry attributes’ function. This process was completed for all seven abandonment plans and the data for each polygon was exported as a CSV file and analysed in MS Excel.

5.3.2.1 Assumptions for Method 2

There were fewer assumptions with this method as the volume was being calculated directly from the abandonment plans. However as with Method 1, this method assumed that the original abandonment plans were a complete and reliable record of the underground void spaces and seam thicknesses for each colliery, and that there were not any additional panels or seams that were not included in the abandonment plans. This method could distinguish between the total volume (including stone mines) and the volume of coal mined, however only the total volume was relevant for resource estimates.

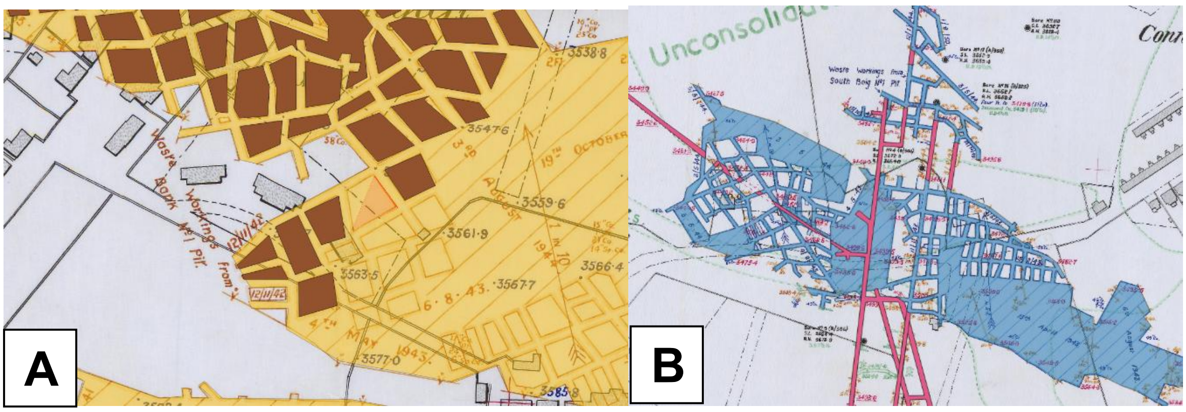

Figure 5.11: Screenshots from QGIS of digitisation of the Seaforth Colliery abandonment plans, both from 22nd August 1955. Figure A shows the polygon created around the outside of the mine workings in transparent yellow and the solid brown polygons that represent the pillars left by ‘pillar and stall’ working. These areas are removed from the yellow polygon using the ‘Difference function’. This is an extract from plan 2 of 7, Eight Feet Coal Workings, and shows the mined-out area of the Eight Feet Coal seam. The buildings shown in that section of the plan are that of Bankglen. Figure B shows the mined-out areas of coal in blue and the ‘stone mines’ in red. For Seaforth Colliery, 7% of the total volume comes from the stone mines. This an extract from plan 5 of 7, Four Feet Coal and Diamond Coal workings, and shows the mined-out area of the Four Feet Coal seam. (MRA, 2023d).

5.3.3 Method 3: Historical coal output data

The coal output in tons was used as a proxy for the volume of the mined-out void left behind. This method did not consider the (waste) rock which would have also been extracted alongside the coal, only the volume of coal that was mined, so was an underestimate of the total void volume. Hahn *et al.* (2019) calculated the volume of Markgraf II Colliery in Bochum, Germany (as described in Chapter 2.3.1.3) by dividing the mass of coal mined (output in tons) by the density of coal, which was taken to be 1.35 g cm^{-3}. For analysis in this study, the method was later refined to include different densities of coal (see Section 5.5.1.3).

The historical data used for this method comes from *'Scottish Collieries: an inventory of the Scottish coal industry in the nationalized era'* by Oglethorpe (2006), a book that compiles data from surveys completed by colliery managers for all Scottish collieries that were operational at the time of the nationalisation of the British coal industry in 1947. The data in this book is split by historical county and numerical data, such as opening year and annual output, is provided for each colliery, as well as some notes about the colliery and events that had occurred there. The data fields from Oglethorpe (2006) are summarised in Appendix 10.5.

To calculate the entire volume of a mine, a lifetime output of coal was needed, however Oglethorpe (2006) only provides an annual output for each colliery, presumably just for the year the survey was completed, although this detail is not made clear in the book. Therefore, for this analysis, to calculate the lifetime coal output of a colliery (in imperial tons), the output per annum (in tons) was multiplied by the lifetime in years of the colliery (date closure – date opened). It has been assumed that the tons given in Oglethorpe (2006) are imperial tons, given the year that the data were collected. This assumes a constant annual production rate for the full lifetime of the colliery. Imperial tons were later converted to metres cubed.

5.3.3.1 Assumptions for Method 3

This method made several assumptions that affected the volume estimation. Firstly, it assumed that the output per annum given in 1948 was the constant annual output throughout the lifetime of the colliery. In reality this will have varied a lot throughout the lifetime of the mine depending on technological advances, geological conditions and economic factors (discussed further in Section 5.4.2.3). Secondly, it assumed that when a mine was listed as a surface mine, that it was an underground mine driven from the surface and not opencast workings (see Section 5.5.1.1).

5.4 Results & Discussion Part One: Individual collieries

The results and discussion for this chapter will be split into two parts. The first part will report the results for the three methods applied to the four collieries discussed in Section 5.2 and interpret the results and discuss any limitations with the three methods. The second part (Section 5.5) will use the three methods to calculate a volume for Scotland as a whole.

5.4.1 Part One: Results

The three methods discussed above were used to calculate volume and the coefficient of variation (COV) was calculated to show how variable the three estimates for each colliery (Table 5.2). The higher the COV the more variation between the three estimates.

Table 5.2: Comparison of all three methods of volume estimation. The method that gives the highest volume for each colliery is highlighted in bold.

Colliery	Volume estimate methods (m^3)			Range (m^3)	Mean (m^3)	Standard deviation (m^3)	Coefficient of variation (SD/mean) x100
	Method 1 (Large scale digitisation)	Method 2 (Individual digitisation)	Method 3 (Historical coal output)				
Seaforth	96,569	**1,059,383**	567,477	962,814	574,476	482,445	84
Cardowan	**17,207,025**	12,455,362	17,008,510	4,751,663	15,556,966	2,687,901	17
Barony	5,234,950	**26,690,444**	22,593,719	21,455,494	18,173,038	11,390,407	63
Killoch	**22,086,758**	16,863,798	20,320,800	5,222,960	19,757,119	5,222,960	13

Seaforth Colliery had the most variable estimates with a COV of 84. This variation could be attributed to only the two deepest seams (Musselband and Blackband) being included in the MRA shapefile, which meant that Method 1 gave a significantly lower estimated volume of 96,569 m^3. Method 2 estimated the total volume of Seaforth Colliery to be 1,059,383 m^3 with mined-out coal having a volume 988,256 m^3 accounting for 93% of the total volume. The remaining 7% (71,127 m^3) of the volume was from stone mines. Method 3 estimated a calculated coal volume for Seaforth Colliery of 567,477 m^3, which was nearly half that of Method 2. Barony Colliery was the next most variable colliery with a COV of 63. Barony had the highest range of 21,455,494 m^3, due to the significantly lower estimate given by Method 1 of 5,234,950 m^3. Methods 2 and 3 gave similar estimates of 26,690,444 m^3 and 22,593,719 m^3. Cardowan colliery had a COV of 17, meaning that the estimates were more similar. The highest estimate of volume for Cardowan Colliery was 17,207,025 m^3 from Method 1 and the lowest estimate was 12,455,362 m^3 from Method 2. Method 3 gave an estimate of 17,008,510 m^3 which is very similar to that of Method 1. Killoch Colliery had the lowest COV of 13 meaning that the volume estimates were most consistent of the four collieries. The highest volume estimate for Killoch was 22,086,758 m^3 given by Method 1, and the lowest estimate was

16,863,798 m^3 given by Method 2. For Method 3, the annual output for Killoch Colliery is not included in Oglethorpe (2006) as it opened after nationalisation in 1960. However, the 'Other details' section of the entry for Killoch in Oglethorpe contains details of how Killoch was the first the Scottish first colliery to reach an output of one million tons per year in 1965 (Oglethorpe, 2006, pg. 82). If one million tons is taken to be consistent throughout the 27-year lifetime of Killoch then this would give a lifetime output of 27,000,000 tons which equates to 20,320,800 m^3 (Table 5.3). However, we know that it reached an output of 1 million tons in 1965, meaning that for the five years prior the output would have been lower. Therefore, if it is assumed that between 1960 and 1964 the annual output was 900,000 tons and from 1965 onwards the annual output was 1 million tons. This would make the lifetime output of the colliery 26,500,000 tons which is equivalent to 19,944,489 m^3. This adjustment does not affect the COV and it remains at 13

Table 5.3: Volume estimates calculated from the data in Oglethorpe (2006) using Method 3. Calculated values indicated by an asterisk*. ** the lifetime output for Killoch Colliery has been estimated from data given in Oglethorpe (2006) that Killoch had reached an annual output of 1,000,000 tons by 1965, see text for explanation.

Colliery name	Production years			Output in imperial tons		*Lifetime output (metric tons)	*Estimated volume (m^3)
	Start	End	*Lifetime	Output per annum	*Lifetime output		
Seaforth	1940	1953	13	58,000	754,000	766,094	**567,4779**
Cardowan	1929	1983	54	418,500	22,599,000	22,961,488	**17,008,510**
Barony	1910	1989	79	380,000	30,020,000	30,501,521	**22,593,719**
Killoch	1960	1987	27	1,000,000**	27,000,000	27,433,080	**20,320,800**

5.4.2 Part One: Discussion

The estimates of volume from this analysis are highly variable and follow no consistent pattern between the three methods, i.e. one method does not give a consistent over or underestimation of volume. The results can be split into two types, as demonstrated in Figure 5.12. Firstly, Barony and Seaforth collieries follow a similar pattern, in that the large-scale digitisation method (M1) gave a significantly lower estimate of volume compared with the other two methods, and the individually digitised plans (M2) gave the highest volume estimate. These two collieries have high coefficients of variation (63 and 84 respectively). Conversely, for Killoch and Cardowan collieries the methods gave a much more consistent estimate of volume, resulting in low values of COV (13 and 17 respectively). In both cases, Method 1 gave the highest estimate and Method 2, gave the lowest. The historical coal output (M3) was always the middle estimate of the three methods for all four collieries.

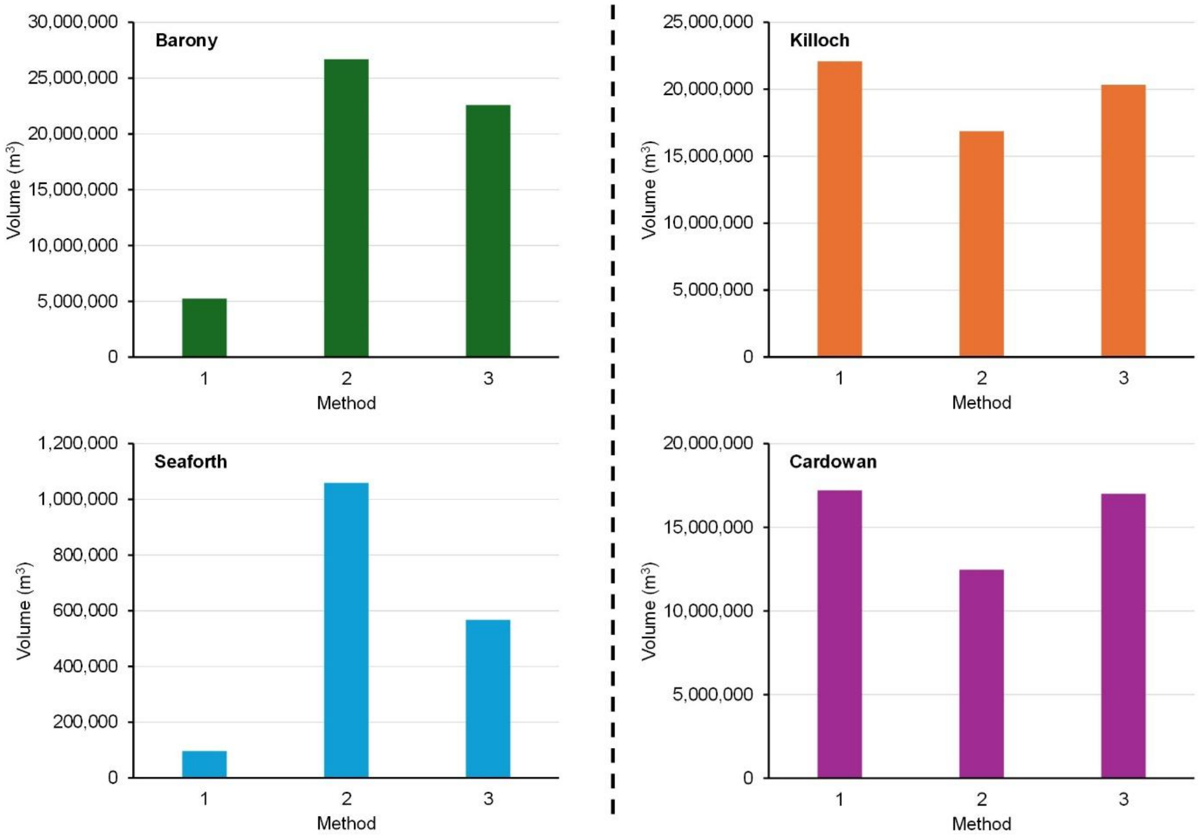

Figure 5.12: Comparison showing the two modes of variation. Each graph has its own y-axis scale.

Of the three methods, individual digitisation (M2) is the most reliable at converting existing plans into digital data. As outlined in Section 5.3.2.1, Method 2 relies on the accuracies of the original coal mine abandonment plans. Additionally, this method relies on accurate georeferencing. For example, through the georeferencing process the plans may not quite be at the right scale or may have slightly changed in size, meaning that the area calculated from those plans may not be accurate to the original plan. This will be a bigger problem with the older maps because there will fewer surface features which remain to the present day to allow for accurate georeferencing.

A major limitation with Method 2 is the time-consuming nature of digitising the abandonment plans, which requires quite a good working knowledge of QGIS and the ability to interpret the abandonment plans. It took the author approximately one week to digitise the seven abandonment plans for Seaforth Colliery, which was the smallest of the collieries and was relatively straightforward to digitise. Some mines are much, much larger and more complex so would take longer to digitise. If the abandonment plans for the 265 collieries listed in Oglethorpe (2006) were digitised using this method, each taking one week, it would take five person-years to digitise them all. However, Seaforth is a small colliery, so this is a minimum.

Despite these limitations, Method 2 is likely to able to give the closest representation to the ‘true’ or ‘known’ volume of the mine. Because of this you would expect that Method 2 would be consistently the middle value of the three, as it will neither over nor underestimate the volume. However this is not the case. For Barony and Seaforth, it gives the highest estimate, but for Cardowan and Killoch, it gives the lowest (Figure 5.12). Rather than highlighting a problem with Method 2, this split between shows two fundamental limitations of Method 1, and by extension the MRA dataset: Method 1 both underestimates and overestimates the ‘true’ volume.

5.4.2.1 Method 1 underestimate due to missing panels

For Barony and Seaforth collieries, Method 1 gives a significantly lower value of volume. Method 1 relies heavily on the MRA database being complete and including all seams for each colliery. Table 5.4 shows the named seams in the MRA database for Barony and Seaforth, as well as the seams named on their respective abandonment plans. Seaforth only has two out of seven seams included in the MRA database. Barony has four seams attributed to it in the MRA database and Otalega *et al.* (2022) names eight seams from the abandonment plans, but only one seam (Musselband) is common to both data sources (Table 5.4). These inconsistencies partially explain why Method 1 gives a significantly lower estimate because not all seams were included.

This further demonstrated by the number of individual panels in the MRA database, where there are only has 30 panels which are named as belonging to Barony (Appendix 10.6). It is highly unlikely, given the age and scale of the colliery, that Barony only had 30 worked panels. When you look at the spatial data on QGIS there are a lot of panels surrounding the area of Barony, but all are ‘unnamed’ so were not included by the ‘extract by attribute’ function. Just because they are in the vicinity doesn’t mean that they can automatically be attributed to Barony, as there were other major collieries in close proximity such as Highhouse and Killoch, which we know was joined to Barony’s workings underground.

This is a problem with the MRA database which could lead to significant underestimates for collieries across Scotland that have panels which not been properly named in the database. Across the entire database for Scotland there are 6235 panels which are unnamed (or a variation thereof), 16% of the total panels in the dataset. This equates to 589,359,913 m^3 of volume that is not attributed to a specific colliery.

In the case of Seaforth, only six panels are named Seaforth in the ‘colliery’ data field and even when you look on the map, with no unnamed panels in the area, there are only those six panels, suggesting that the five other seams were never digitised and added to the database. Figure 5.13 demonstrates how much of an underestimate these missing seams caused for

Seaforth Colliery. The Method 2 estimate is over ten times larger than Method 1. Even for the seams that the MRA have got, the volumes are not consistent with the abandonment plan data. The volume for the Blackband seam is in the same range as that of the abandonment plan (64,911 m^3 compared with 77,258 m^3) but the volume for the Musselband seam is significantly smaller than that of the abandonment plans (32,450 m^3 compared with 249,963 m^3; Figure 5.13).

There is an inherent similarity between Barony and Seaforth, it is likely just coincidence that they both had significant portions of their abandonment plans missing from the MRA database. However, these two collieries alone have shown how unreliable the MRA underground workings dataset is for estimating volume at a regional or national scale.

Table 5.4: Comparison of the panels from the MRA underground workings dataset (MRA, 2023c) and the panels on abandonment plans for Seaforth and Barony collieries (MRA, 2023d, Otalega *et al.*, 2022). Seams common to both data sources are highlighted in bold.

Colliery	**Named seams in MRA dataset (MRA, 2023c) (M1)**	**Seams on abandonment plans (M2) (MRA, 2023d, Otalega *et al.*, 2022)**
Seaforth	• **Musselband** • **Blackband**	• Five Feet • Eight Feet • Three Feet • Four Feet • Diamond • **Musselband** • **Blackband**
Barony	• Diamond • Lugar main • **Musselband** • Knockshinnoch	• Ell • Main • Major • Ayr Hard • 40 fathom • 36 fathom • **Musselband** • 20 fathom • 17 fathom

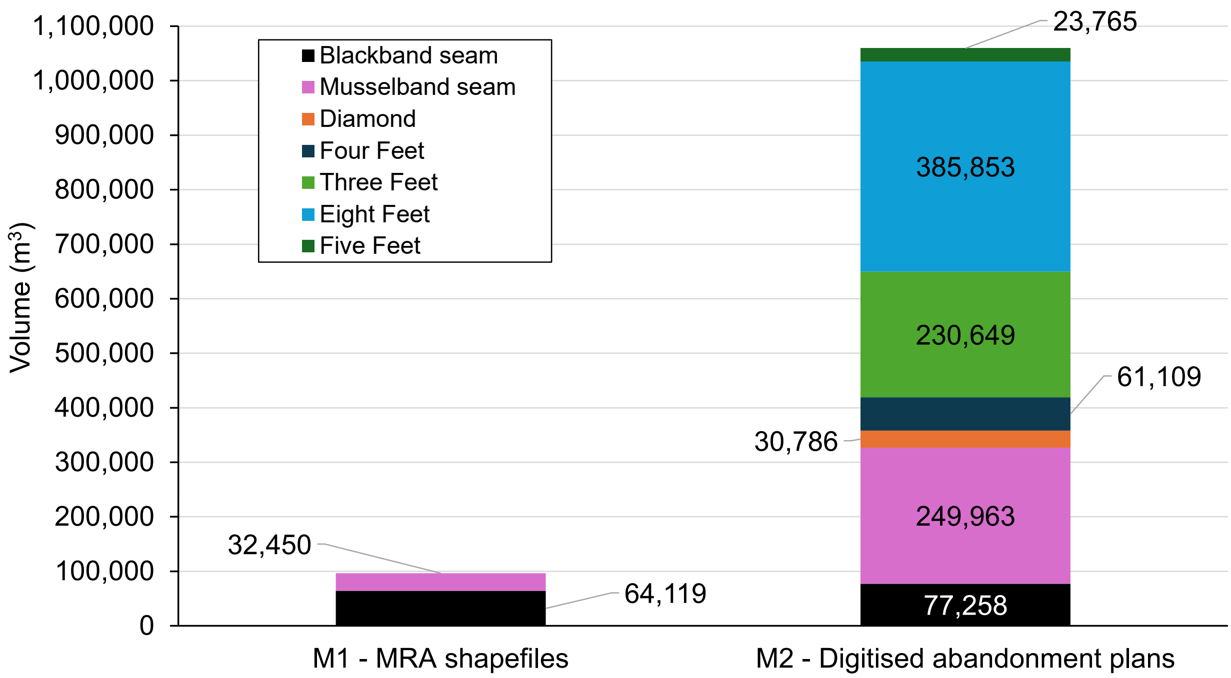

Figure 5.13: Comparison of total volume calculated by Method 1 and 2 for Seaforth Colliery split by the individual seams. The total volume calculated by Method 1 is 96,569 m³ and the total volume calculated using Method 2 is 1,059,383 m³. The data labels show the volumes of the individual seams in cubic metres (m³).

5.4.2.2 Method 1: overestimate due to lack of granular detail

For Cardowan and Killoch, Method 1 gave a volume estimate larger than Method 2 which is likely to be an overestimate. These shapefiles are outlines of the mined-out panels without more granular details such as pillars (from pillar and room workings). This means that the volume calculated from the outline will be an overestimate of the area of the panel, and therefore of the volume. Coal seam thicknesses vary spatially, so by using seam thickness to calculate volume instead of density, the estimate of volume for specific mines will be more accurate. This means the MRA data either include a lot of polygons that should be pillar and room, or have overestimated the thickness, or both.

The underground workings dataset began in the 1980s, when abandonment plans were georeferenced to Ordnance Survey maps and rationalised by mining surveyors from the NCB and British Coal (BC), in order to automate the provision of coal mining reports, became available nationally in 1989 (MRA, 2015). The dataset guidance states that: *"Due to the primitive emerging GIS technology available at the time of initial capture and the primary purpose of the capture being the automated provision of coal mining reports, the rationalised plans show a simplified version of the information contained on the abandoned mine plans"* (MRA, 2015, pg.8). The rationalised plans were subsequently digitised for the National Coal

Mining Database in 2011. In 2023, the dataset was uploaded onto the Edina Digimap as GIS shapefiles (MRA, 2023c).

When I spoke to the MRA about this data, they informed me that there were a lot of regional differences between the rationalisation of the abandonment plans, even between individual surveyors, as they were done by regional offices of the NCB and that they are often over generalised and don’t include granular details such as pillar and room workings. They also said that these data were not originally collected for research purposes but for the conveyancing process and such overgeneralisation is not a problem for that. They identified that this data contains poor quality digitisation and edge matching problems. The MRA and they are aware of the inaccuracies within this dataset and that it affects their own research. They were happy that the seam thickness was “well constrained” and that the seam thicknesses reported in that dataset are accurate.

5.4.2.3 Method 3: overestimate due to variation through time

It stands to reason that Method 3 would consistently be the lowest of the three estimates, as it cannot account for rock that was mined alongside the coal, or for roadways. However, for Cardowan and Killoch collieries the opposite is true. Method 3 unexpectedly gives a higher estimate than Method 2 (Figure 5.12), thus exposing the main limitation of using historical coal output data from Oglethorpe (2006). It suggests that the annual output reported in 1948 was higher than the output in the years thereafter. i.e. the coal output decreased over time after 1948.

The data compiled by Oglethorpe (2006) is from a survey filled out by colliery managers in 1948 and 1949 after the nationalisation of the coal industry in 1947 (Chapter 2.4.2). A single value was given for the output per annum (tons) and presumably will have been the annual output in 1948 or 49. There is no further information on whether this was close to the peak production, or if an individual colliery was in decline. The peak year and the peak output are both unknown[14]. Due to only having a single output value for each colliery, the calculated lifetime output has to assume that the output remained constant throughout the lifetime of the colliery (see Section 5.3.3.1). However this is not realistic, and it is more likely that the output of the collieries increased over time until reaching a peak and then trailing off. Therefore, for any year the actual output was less than the value reported in 1948, Method 3 will overestimate

[14] Oglethorpe (2006) includes for each colliery, the average and maximum workforce and the year of the maximum, but the timing of the data collection is unclear (some maxima are from later than 1948). However, maximum workforce does not necessarily corelate with peak coal production however due to advances in mining technology like mechanical coal cutting (Duncan, 2005), so cannot be used as a proxy to estimate peak output.

the volume, and vice versa. The output will vary for each colliery based on its history. Figure 5.14 shows a hypothetical graphical example of this concept.

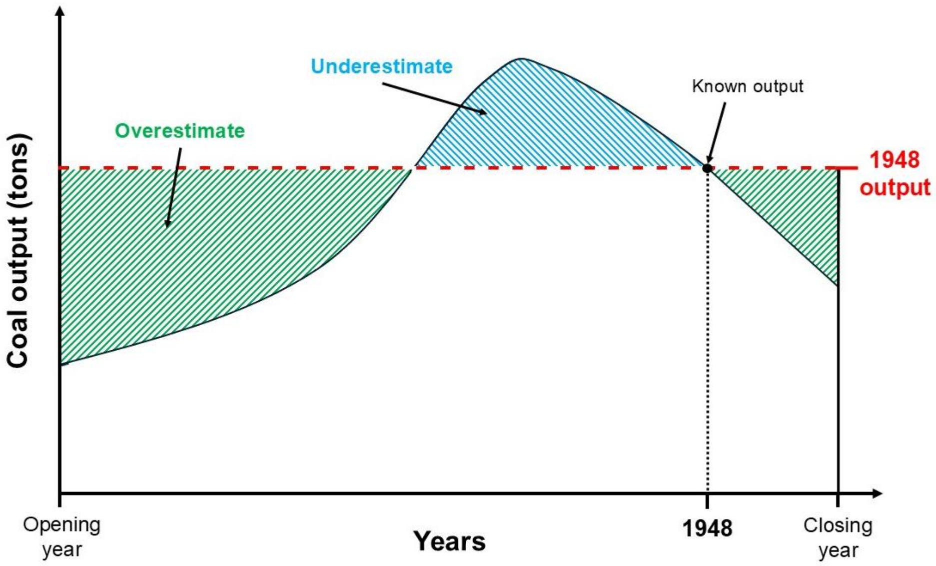

Figure 5.14: Diagram showing the potential for over and underestimation in Method 3. The x-axis is output in tons, and the y-axis is year. The dashed red line is the constant 1948 output. The solid black line is the 'actual' output (which cannot be known). The green hatched areas show when using the 1948 value would give an overestimate of volume as the 'actual' mass is less than the 1948 output. The blue hatched areas show areas where the 'actual' output is more than the constant 1948 value and therefore would make the volume estimate an underestimate. Drawn by the author.

An example of a colliery with a highly variable coal production history is Barony which was open for 79 years. Figure 5.15 shows an estimated representation of the coal output over its lifetime, based on the historical information described in Section 5.2.3. Oglethorpe (2006) gives a daily output for Barony of 1520 tons and an annual output of 380,000 tons[15] (Oglethorpe, 2006, pg.70). We also know from Oglethorpe that the third shaft, completed in 1949, was built to increase the output from 1500 tons to 2500 tons per day (Oglethorpe, 2006, pg.70). Therefore, throughout the 1930s until the late 1940s, the output must have been around 1500 tons per day, which gives an annual output of 375,000 tons, which is very close to the 1948 output. The third shaft opened in 1949, so the colliery probably had a period of higher output following this. If the desired output of 2500 tons was achieved for 250 days per year[15], that would give an annual output of 625,000 tons. During this period, Barony increasingly also took on many miners from surrounding collieries in Ayrshire which had closed, reaching a peak of 1695 workers in 1958 (Oglethorpe, 2006, pg. 70). This would have

[15] meaning that the colliery was operational for 250 days a year.

presumably led to an increased coal output. Following the collapse of Shaft No.2, Barony was closed between 1962 and 1966 so the output for those four years would be zero (meaning the 1948 estimate is definitely an overestimate for those years). In the aftermath of the disaster, Shafts No.1 and No.2 were filled in, and a new shaft was sunk, meaning in 1966, the colliery went back to operating with two shafts rather than three, so the output probably returned to outputs seen in the 1930s and 40s. In the 1970s and 80s Barony faced many geological difficulties and problems with understaffing (Section 5.2.3), so it is likely that the output decreased over those two decades until Barony's closure in 1989.

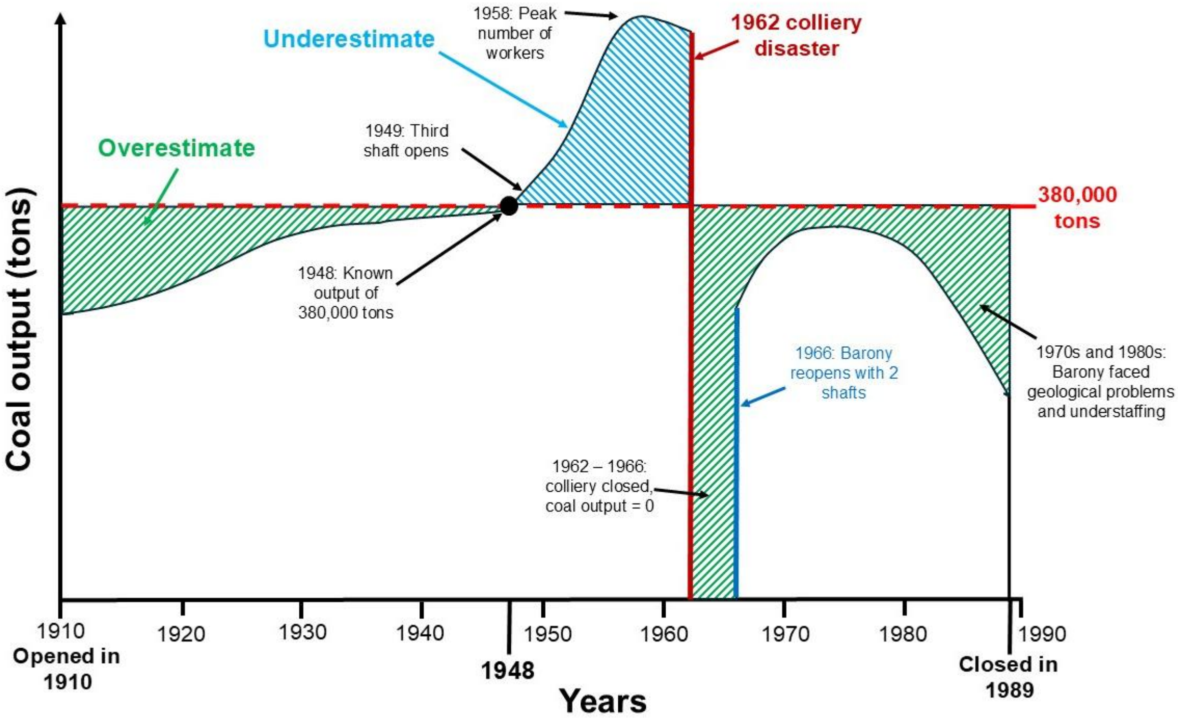

Figure 5.15: Diagram for the theoretical lifetime coal output for Barony Colliery with significant events labelled. Colours are the same as Figure 5.14. Drawn by the author.

5.5 Results & Discussion Part Two: Scotland-wide estimates

These three methods could all, in theory, be used to estimate of the total mined-out volume across Scotland. As discussed in the Introduction, estimating the total theoretical minewater energy resource for Scotland could be useful to incentivise investment and technology development. This would be particularly relevant to national governments interested in knowing the total theoretical minewater resource available to them, whereas the individual colliery estimates would be relevant to local authorities, landowners, or developers.

5.5.1 Part Two: Methods

This section will outline how Methods 1 and 3 were used to calculate a volume for the whole of Scotland. Due to the large number of abandonment plans, the time taken to digitise them (Section 5.4.2), and the ability to access all of them, it is not practical to use Method 2 for a national estimate and doing so is beyond the scope of this research. To use Method 1 to calculate the volume for the whole of Scotland, the calculated volumes (described in Section 5.3.1) for each of the individual 31,201 coal mine panels are summed together. The assumptions remain the same as discussed in Section 5.3.1.1.

To use Method 3 for a nationwide estimate, the volume from all 265 collieries listed in Oglethorpe (2006) would need to be summed together. However, not every colliery listed had a complete set of data, so for a colliery to be included in this analysis, it needed to have:

- The years that production commenced and ceased, in order to calculate a lifetime of coal production.
- Annual coal output data, given in imperial tons.
- Must represent underground workings rather than opencast workings (see Section 5.5.1.1)

Applying these criteria to the dataset led to 62 collieries being discounted from the analysis, leaving 202 remaining collieries for the volume estimates.

5.5.1.1 A note on terminology used in Oglethorpe (2006)

According to the glossary in Oglethorpe (2006) a ‘surface mine’ is defined as: *“In Scotland, a term often used to describe an Incline or Drift Mine, where a tunnel is sunk into the ground following the incline of the strata. In some parts of the world, the term surface mine is used to define open-cast workings.”* (Oglethorpe, 2006, pg. 289). Drift mine or ‘Drift’ is defined as: *“a horizontal or near-horizontal underground drivage from the surface that follows along the length of a seam, vein or rock formation. It serves the same purpose as a shaft but is usually considerably cheaper”* (Oglethorpe, 2006, pg. 277). Therefore, for this analysis collieries that were listed as being 'surface mines' and had details of the shafts, were presumed to be underground workings and not opencast mines.

5.5.1.2 Limitations with Method 3

One limitation with using this method to calculate a national volume is that Oglethorpe does not include all collieries that ever mined coal in Scotland and not all the collieries listed could be included in the analysis as they had insufficient data (62 discounted). Additionally, there are some inconsistencies in which collieries were included. For example, three collieries which had closed before nationalisation on 1st January 1947 were included, as well 56 that were opened after nationalisation (Figure 5.16). It is unclear why these are included in the book, as they did not exist at the time of nationalisation.

As discussed in Section 5.4.2.3, the main limitation of this method is only having one datapoint to represent the entire history of a colliery. There is a wide range of colliery ages included in this analysis, spanning over 200 years. The oldest colliery in the dataset is Fordell in Fife which opened in the 1750s, (Oglethorpe, 2006) right up to Castlebridge Colliery in Clackmannanshire, which was part of the Longannet Complex and was sunk 1978 (Scottish Mine and Cave Database, 2024). For the early coal mines, coal outputs will have been much lower: mines were much smaller, could not have gone as deep due to lack of water pumping technology, and mining was only mechanised in the latter half of the 19th century and didn't become widespread in Scotland until the 20th century[16]. The majority of collieries in the dataset (238, 90%) remained open after nationalisation in 1948 and with technological advances the output of these collieries may have increased over time, and the outputs after 1948 may have been much higher than the output for most of the lifetime of the mine. This is especially for those which were became operational during the 1960s, after the NCB's introduction of 'Superpits' which aimed to increase production (Duncan, 2005). Conversely output may have decreased over time as seams became worked out. Output may also have been affected by economic and societal factors such as the price of coal, demand for specific types of coal (e.g. for the steel industry or domestic use) and employment factors.

[16] The first electric coal cutter was used in 1842 (MRA, 2018) and only started being used in Scotland in the 1890s (Duncan, 2005). By 1913 there were 900 mechanical coal cutters in operation in Scotland (Duncan, 2005).

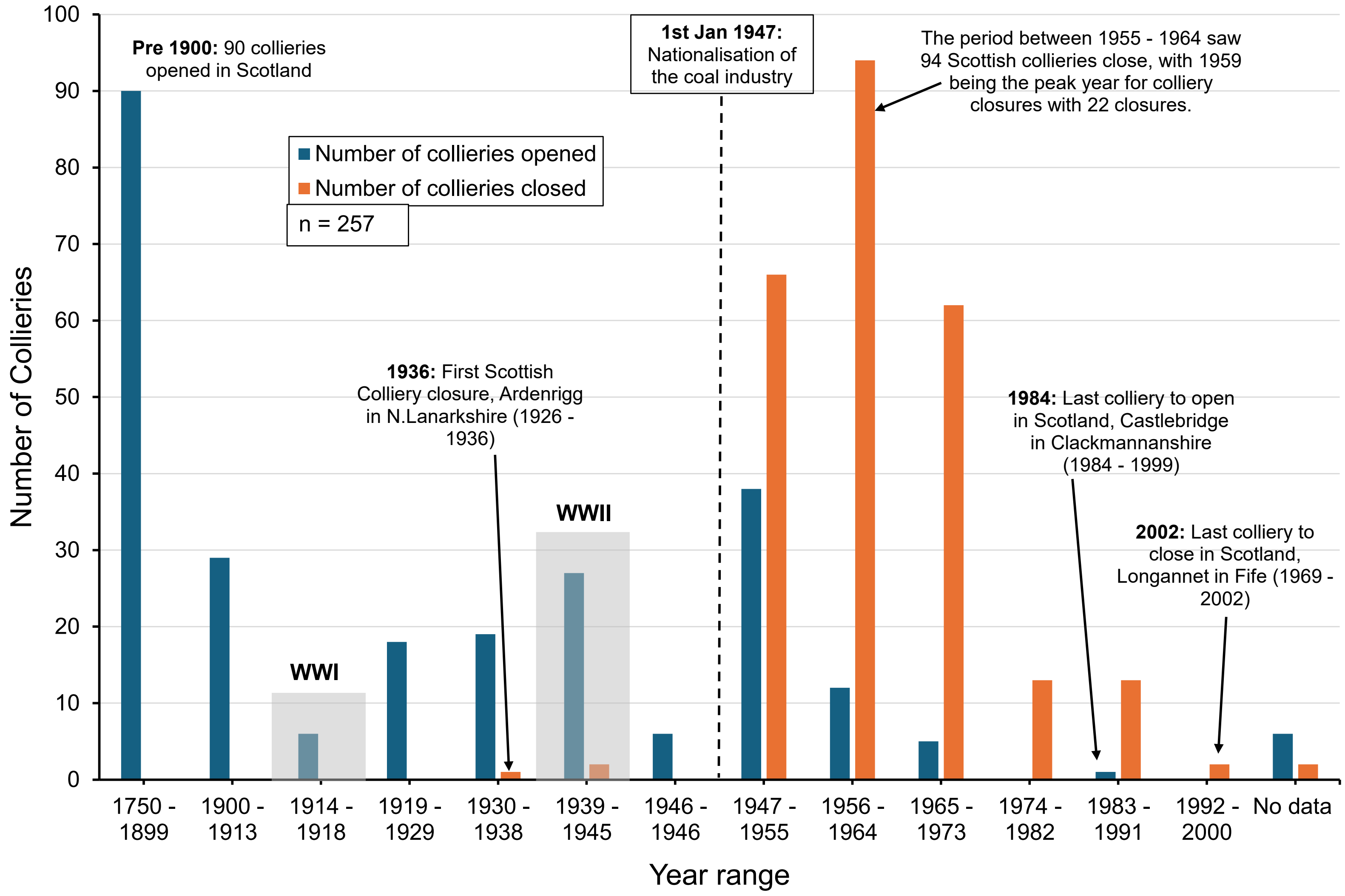

Figure 5.16: Plot of opening and closing dates for Scottish collieries organised by historical events. For clarity, collieries opened in the 18th and 19th centuries (pre-1900) have been grouped together. Five collieries had no data for opening date, one had no data for closing date, and one had no data for both opening and closing date. Contains data from Oglethorpe (2006).

5.5.1.3 Method 3: Density of coal

As well as output in tons, the volume calculations in Method 3 are based on the density of coal. In Scotland, the main type of coal mined was anthracite or bituminous coal which had multiple colloquial names such as house, coking, or steam coal (Table 5.5). Anthracite and bituminous coal have a density of between 1.36 – 1.80 cm^{-3} and 1.25 – 1.5 g cm^{-3}, respectively (Xie, 2015). Anthracite is more dense and would therefore equate to a slightly smaller void volume per mass of produced coal than bituminous coal. For the original analysis a density of 1.35 g cm^{-3} was used for all collieries (Hahn *et al.*, 2019).

Different collieries mined different seams of coal, which had different densities. Oglethorpe (2006) provides a list of the types of coal mined for each colliery and does not specify the proportions of each type of coal. There were 53 different combinations of coal types across the 202 collieries, with one to five types of coal per colliery. For this analysis it was assumed that each colliery mined equal quantities of the types of coal listed in its entry. For example, if a colliery was listed as mining two types of coal, the proportion of each would be 50%, if there were three types of coal it would be 33% each, etc. The bulk density of the coal was then calculated from the average density of the different coal types. For example, if a colliery was listed as mining anthracite and coking coal (bituminous), then 50% of the density would be anthracite which has an average density of 1.58 g cm^{-3} (Table 5.5) and 50% of the density would bituminous coal with a density of 1.35 g cm^{-3}. This gives an average density for that colliery of 1.47 g cm^{-3}. The most common combination of coal was 'house and steam', both of which are bituminous coal, with 66 collieries listed as mining that combination. Only 15 collieries (6% of total collieries) were listed as mining only anthracite. The only seam that was specifically named in Oglethorpe (2006) was the 'Upper Hirst' seam, which was commonly mined in central Scotland (McLean, 2018).

Table 5.5: Summary of types of coal mined in Scotland and their densities.

Type of coal	**Density (g cm^{-3})**	**Description**
Anthracite	1.36 – 1.80 (av. = 1.58) (Xie, 2015)	*"Hard and very brittle, dense and shiny black with no marks or layers"* (Mobley, 2001)
Bituminous **Also known as:** Steam coal, house coal, coking coal, gas coal, manufacturing coal (Kopp, 2019).	1.25 – 1.5 (av. = 1.375) (Xie, 2015) 1.35 (Hahn *et al.*, 2019)	A dark brown to black, layered coal, which when heated becomes cohesive and sticky (Mobley, 2001, Kopp, 2019). Bituminous coal is the most abundant form of coal, has a high heat value and low moisture content, and is easy to store and transport (Kopp, 2019).

5.5.2 Part Two: Results

Method 1 (large-scale digitisation) gives an estimate of 3,798,070,968 (3.79 km^3) and Method 3 (historical coal output) gives an estimate of 1,153,626,396 m^3 (1.15 km^3; Table 5.6). For Method 3, when the type of coal is considered for each individual colliery, and the different densities are used to calculate volume, the total volume for Scotland is 1,147,212,331 m^3, (1.14 km^3), only a 0.6% decrease from the original calculated volume (Table 5.6). The estimate from Method 1 is over three times greater than the estimate from Method 3 and the discrepancy between the two estimates is 2.6 million cubic metres.

The Department for Energy Security and Net Zero (DESNZ) publishes annual historical coal output data for the UK, starting from 1853 (DESNZ, 2024). Based on a total UK production of 15 billion tons, the volume estimate for the whole of the UK is approximately 11 billion m^3. Table 5.6 shows the percentage of that total each estimate represents of that total: Method 3 accounts for 10% of the total UK volume, and Method is 34% (Table 5.6).

Table 5.6: Comparison of estimates from Methods 1 & 3 for the total mine volume for in Scotland. The estimated total UK volume of 11 billion m3* comes from the DESNZ data on historical coal production: 15 billion tons, total mass of coal mined in the UK (DESNZ, 2024).

Method	Estimated total volume (m^3)	Percentage of estimated total UK volume*	Data Source
Method 1	3,798,070,968	34%	Mining Remediation Authority shapefiles (MRA, 2023c)
Method 3	1,153,626,396	10%	Coal output data (Oglethorpe, 2006) and a coal density of 1.35 g cm^{-3} (Hahn *et al.,*2019)
	1,147,212,331		Considering individual colliery coal density data as described in Section 5.5.1.3.

5.5.3 Part Two: Discussion

The large difference in volume between the methods suggests that one or both are a large over or underestimate. By comparing historical coal output data for Scotland from between 1854 and 1988 (Dron, 1901, Moore, 1950, Halliday, 1990) with historical UK coal production (DESNZ, 2024), on average Scotland accounted for 11% of total UK coal production, with a range from 17% in 1913 to 2% in 1988. 11% of 11 billion m^3 is 1.2 billion m^3 which is very similar to the Method 3 estimates of ~1.15 billion. Scottish coal production never reached proportions as high as 34% as suggested by Method 1, suggesting that this is a huge overestimate[17]. As with the individual collieries (Section 5.4.2.2), this is likely due to the fidelity and granularity of the shapefile data and suggest that many polygons for pillar and room workings have not removed the pillars from the overall panel. The MRA informed me that they were happy with the seam thicknesses in the underground dataset and given that each panel was calculated from its individual seam thickness and an area, the problem lies with the area.

Theoretically, Method 1 includes all mined out coal across the whole lifetime of the collieries, as it reflects the abandonment plans, hence why it is a much larger value than Method 3. However, it is incredibly unlikely (impossible) that 3.54 billion tons (2,644,444,572 m^3) of coal were mined in Scotland between 1948 and 2002. Over this 54-year period that would equate to an average annual coal output of 65.6 million tons per year[18]. We know from Moore (1950) that the peak year for coal output from Scottish collieries was 42 million tons in 1913, and that by 1946 it had reduced to 22.5 million tons per year. This would make Method 1 a huge overestimate of the true volume.

As discussed in Section 5.4.2.3, Method 3 is relying on a single datapoint from 1948 to interpolate coal output for the entire lifetime of the colliery. This would suggest that Method 3 would be an underestimate of the 'true' volume because coal mining in Scotland continued for another 54 years, until 2002. Additionally, the data in Oglethorpe (2006) was only sufficient 202 out of the total 265 collieries in Scotland. These 265 collieries might not also have been all the collieries in Scotland; there may be others which were not included by Oglethorpe. The different density of coal used in Method 3, made very little as most collieries were mining bituminous coal and only 15 mined anthracite.

[17] Method 1's estimate of volume is equivalent to 5,103,359,519 tons (metric)
[18] In fact, my own estimates (see Section 2.4.3) suggest that around 67.2 million tons were mined in Scotland during the entire 54-year period between 1948 and 2002.

5.6 Conclusions

The analysis shows that there is no consistent method of calculating volume of underground voids. Digitisation of abandonment plans is most reliable (closest to 'true value' of volume) and has the added advantage of allowing a better understanding of the underground structures.

Historical coal data works as a proxy for volume, but the Oglethorpe (2006) data are not complete for Scotland and there is one data point for each colliery, output in 1948. Output data for each individual colliery could probably be found on paper records in an archive and a recommendation from this analysis is that it is essential to investigate that archival material for collieries which are being considered for minewater thermal energy.

Using the Mining Remediation Authority shapefiles is the fastest method of estimation, but without extra data on the collieries (available from mining records e.g. at the MRA, national museums and archives, or local knowledge) it can lead to significant over or under-estimations. This work demonstrates that initial estimates of mine volume are sufficient to establish the likely volume of a mine but highlights the need for a case-by-case assessment of each mine being considered for minewater thermal resources.

This means that we are no closer to having a consistent method of estimating the volume of a mined-out void, which has implications for the minewater thermal industry. It points, again, to the need to consider each mine on a case-by-case basis. High level regional studies should only be used as an initial estimate of the resource, and that further investigation for individual sites is always needed to narrow down reserve estimates.

5.7 Personal reflection on the digitisation process

Digitising the mine plans myself allowed me to understand the complexity of the mine workings and the different levels of seams, as well as being more confident in my calculations. However, this was a time-consuming process as the mine abandonment plans are very detailed, even though Seaforth Colliery is relatively small compared with other collieries. Digitising the seven plans on QGIS took around one week, before doing any calculations, just drawing round them. This process would be too time consuming for a Scotland-wide study of volume, as many collieries are much bigger than Seaforth. Whilst carrying out the analysis for Seaforth Colliery, I discovered that the Mining Remediation Authority had uploaded their spatial data on underground workings and seam levels onto Digimap where I could download them. Therefore, I decided not to digitise any further mine abandonment plans because I could use the shapefiles from the Mining Remediation Authority. However, I think this was still a useful exercise.

It was suggested to me by several people when I was digitising the plans for Seaforth colliery, “why don’t you just get AI to do it?”. At the time I was digitising these plans in late 2023, artificial intelligence had just started to come into widespread use. I felt that I did not want to use AI for the digitisation, as it would take too long to work out what to do and then go through and check everything that it had done, as I assumed that AI would not know enough about coal mining abandonment plans to be able to make an accurate digitisation of the plans. As I said above, I also found the process itself useful as it allowed me to better understand the structure of the mine and how the abandonment plans worked. Using AI would have taken the knowledge that I gained about that colliery away from me and thus defeated the purpose of doing it in the first place. We shouldn’t rely too heavily on AI for digitisation as I feel that it needs a geologist’s eye to interpret the abandonment plans, many of which contain colloquial terms, local to Scotland.

6. CHAPTER 6: Predicting the future of low-carbon heating in Scotland using housing statistics: A spatial and temporal approach.

6.1 Introduction

As discussed in Chapter 2.1, decarbonising heat is an important challenge not only for the reduction of carbon dioxide emissions but for the improvement of public health, as living in cold, damp homes can cause many negative health outcomes. The housing stock of the UK is the oldest in Europe (Piddington *et al.*, 2020) and people in the UK pay higher electricity bills than many of their European counterparts (HEPI, 2025). By decarbonising heat in a fair and efficient way, many societal problems could be addressed simultaneously.

Currently over two million homes in Scotland use mains gas for heating (Scottish Government, 2023), so in order for the Scottish Government its reach its target of net zero by 2045 (Scottish Government, 2020b), there needs to be a mass replacement of these “polluting heating systems” (Scottish Government, 2023) for electrified heating systems such as heat pumps. There also needs to be a significant reduction in electricity price to avoid pushing thousands of people in to fuel poverty as they decarbonise their heating (Section 3.3.4.4).

Progress towards the decarbonisation of heat has been slow compared to other sectors such as decarbonising electricity generation (House of Commons, 2024). Current research suggests that reticence to move towards low carbon heating systems is multifaceted, with factors such as cost of installation, disruption, and lack of public awareness and confidence in the technology, all affecting uptake (Sovacool *et al.*, 2021; Becker *et al.*, 2023). Insufficient customer demand was seen as the biggest barrier to increasing heat pump installations (Jindal *et al.*, 2024) and other low carbon projects such as minewater thermal (Chapter 3).

Gas boilers currently installed in people’s homes will eventually need replacing and the demand for low-carbon heating systems should therefore increase over time. However, very few people are going to remove a perfectly functional gas boiler and replace it with a heat pump until they have to, because of the cost and inconvenience of doing so. Predicting when households might need to replace their existing heating system could encourage forward planning and allow households to consider low carbon alternatives or form the basis for an advertising and promotion campaign aimed at informing landlords and householders as to the clean-energy alternatives to simply reinstalling a replacement gas boiler.

Awareness of future heat demand could help local authorities to better target resources, allow for more strategic thinking, and could provide confidence to supply chain companies and developers of the scale and spatial concentration of low-carbon heat demand across Scotland. It could also aid in the development of minewater thermal resources, if there is a large demand for low-carbon heat then investment will be more readily obtained. It will also give businesses confidence to invest in training their workers to move away from gas boiler installation and toward heat pump installation. The change from gas to electric forms of heating (heat pumps, heat networks, direct electric) will put more strain on the electricity grid, so knowing when and where heating is going to switch to electric could help to plan upgrades to the grid so that it can be ready. Therefore, the spatial and temporal prediction of heat demand will be crucial for the effective roll out of low carbon heat solutions. We know the current spatial distribution demand for heat from the Scotland Heat Map (Scottish Government, 2020c) but is it possible to forecast how that demand will change over time? This chapter examines the future heat demand in Scotland and develops a method to estimate when and where new heating systems may be required using house building statistics and current heating system type. It aims to determine when and where the peak demand for new heating systems may arise, at a local authority level.

Please note this analysis only considers domestic heating and not commercial or industrial heating, and the terms ‘dwelling’ or ‘home’ throughout this chapter includes all types of domestic dwellings which includes houses, bungalows, and flats.

6.2 Methods

The only time we can know when a dwelling had a new heating system installed was the year it was constructed. Therefore, if year of construction is known, then the age of a building can be therefore used as a proxy to calculate when a heating system may need to be replaced. Using the age of the house and a boiler lifetime it is possible to predict when a boiler will have reached the end of that lifespan and have needed replacing.

Scottish Government have collected data on the number of new build domestic dwellings which were started and completed each quarter, for each local authority area, since Q2 1996 (Scottish Government, 2024e). For this analysis, only the completions were considered, as those are the homes which will have had their heating system installed that year. The data used for this analysis were published in June 2024 and includes data from Q2 1996 up to Q3 2024 (Figure 6.1). However, only complete years were included in this analysis meaning the data range is Q1 1997 to Q4 2023 and is discussed further in Section 6.2.1. As this analysis was carried out in 2024, the age of the buildings is calculated from 2024 minus the year of construction.

In the UK, condensing gas boilers were made mandatory in new buildings on 1st April 2005 through a change to Building Regulations (Department of Trade and Industry, 2003, Eyre, 2020). Therefore, it is reasonable to assume that most houses built during the period of the Scottish Government completion data will have had a gas boiler installed. In their sixth carbon budget, the Climate Change Committee (CCC) assumes a gas boiler lifetime of 15 years (CCC, 2020). In this analysis, modelling has been undertaken for a range of boiler lifetimes around the 15-year CCC lifespan: 5, 10, 15, 20 and 25 years.

Based on boiler lifetime and the age of the dwellings, the ‘generation’ of the boiler can be calculated for each construction year. For example, a house built in 2000 (24 years old) would be on its second boiler because it is over 15 years old, but a house built in 2017 (7 years old) would still be on its first boiler. This gives a ‘replacement year’. For example, the replacement year for homes built in 2000 with second generation boilers would be 2030. This can be calculated for every construction year between 1997 and 2023. Different construction years can have the same replacement year. For example, 1997 and 2012 both have a replacement year of 2027 but with different generations of boilers being replaced. Therefore, it is possible to aggregate the number of replacements in each replacement year starting from 2024, for each local authority. In QGIS, these data were combined with the local authority boundaries to create maps of replacements in each local authority.

Since its installation, a very well-maintained boiler may never have been replaced or may have been replaced early, however for the purposes of this model it is assumed that boilers have been replaced when reached the end of their modelled lifespans. Changing the boiler lifetime does not change the total number of replacements but it will change the years in which the highest and lowest amount replacements fall, and the year that all replacements will have occurred. The year that zero replacements is reached is the lifespan added to the start year of 2024.

This method assumes that for each boiler lifetime scenario, the lifetime remains constant across the 26-year period. However, boiler lifetime probably increased over time as technology improved, e.g. a boiler installed in 1997 may have lasted 10 years to 2007, then its predecessor may last 15 years (2022), and then the third-generation boiler installed in 2022 might last for 20 years. In reality, boiler lifetime is also highly dependent on the quality of the installation and the boiler itself, consistency of services and maintenance, as well as luck.

6.2.1 Housing completion data

Figure 6.1 shows the Scottish Government (2024e) quarterly completion data aggregated to the number of dwellings completed each year, from Q1 1997 to Q4 2023. Between Q1 1997 and Q4 2023, 552,421 new dwellings were completed in Scotland, accounting for 22% of the total Scottish housing stock[19]. The annual number of completions ranges from a high of 25,747 in 2007 to a low of 15,053 in 2012, and the annual average was 20,460 ± 3518 (standard deviation). Figure 6.1 also shows how house building was affected by global events such as the COVID-19 pandemic and the global financial crash of 2008, as they show a dramatic decrease in the number of houses completed.

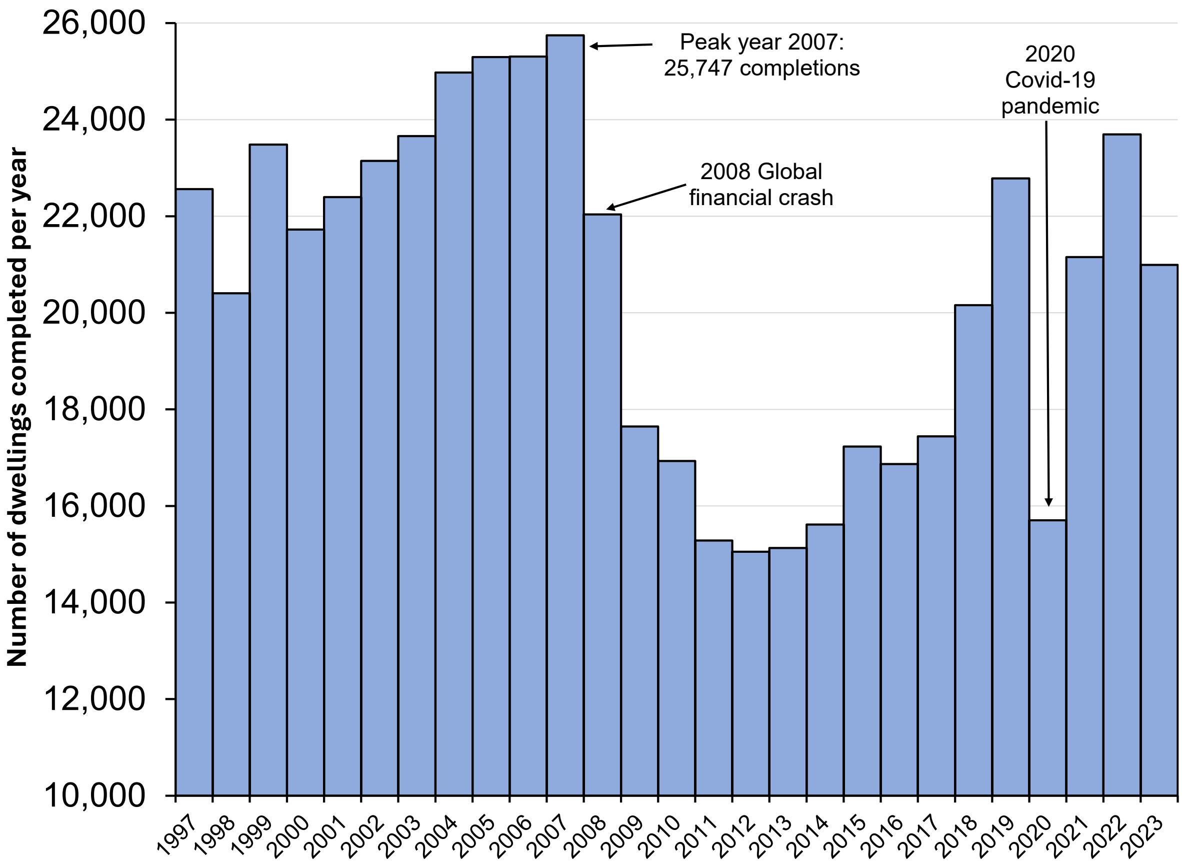

Figure 6.1 Annual new build completion total for Scotland between 1997 and 2023. Data from Scottish Government (2024e).

[19] There are 2,509,275 occupied dwellings in Scotland (Scottish Census 2022),

6.3 Results

The results of this modelling are both temporal and spatial, containing predictions for all 32 Scottish local authorities across the next 25 years. It is important to remember that these values are only for homes constructed between 1997 and 2023, only 22% of the total number of dwellings in Scotland, meaning that the true replacement demand will be much higher, but harder to predict.

6.3.1 Temporal sensitivity analysis

A sensitivity analysis was carried out for five different lifetime scenarios, from a low lifetime of 5 years to a high of 25 years. Figure 6.2 shows the total number of replacements in Scotland each year from 2024 to 2049 for each of the five lifetime scenarios. The 5-year scenario is the most extreme, with an annual average of 110,484 (±12,218 SD) replacements each year between 2024 and 2029. The 15-year scenario has an annual average of 36,828 (± 11,135 SD). It reaches its maximum number of replacements in 2037 with 49,440 replacements and the minimum in 2026[20] with 15,286 replacements (Figure 6.2). The 25-year scenario has the lowest annual average of 22,097 (±7,364 SD) replacements per year. Figure 6.2 shows that the number of replacements in this scenario remains steady from 2024 to around 2042, ranging between 25,747 in 2032 and 15,053 in 2037. Between 2045 and 2047 the number of replacements increased from 15,703 in 2045 to 46,254 in 2047, an increase of over 30,000.

Each scenario has a different maximum replacement year. For the shortest lifespan of five years, 2027 is the peak year with 127,641 replacements, when the life span is 10 years the peak year is also 2027 but with just over half the number of replacements (65,748) compared with the 5-year scenario (Figure 6.2). This trend of decreasing replacement with increased boiler lifespan does not continue, and the 15-, 20- and 25-year scenarios all have very similar maximum (and minimum) replacement years of between 46,000 and 49,500 replacements in the peak year. These scenarios all reach their peak within 10 years of each other, between 2037 and 2047 (Figure 6.2).

[20] 2024, 2025 and 2026 all have lower replacements years as they only have two generations of boilers because there were no data for 1994, 1995, and 1996.

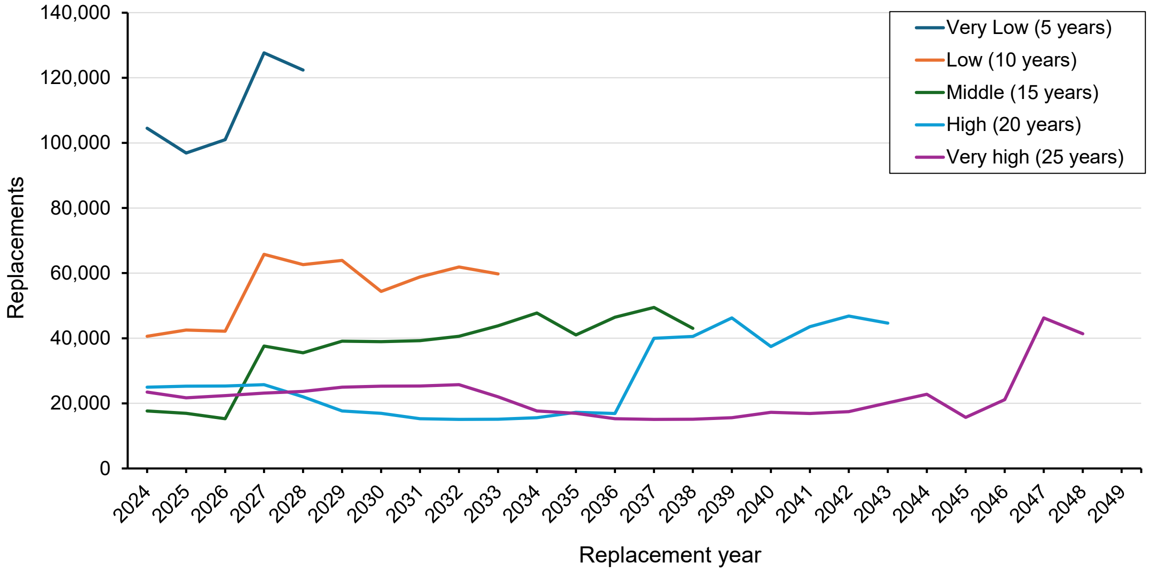

Figure 6.2: Sensitivity analysis between 2024 and 2049 with the five lifetime scenarios.

6.3.2 Spatial analysis

Heating replacements are variable between different locations, as they are a function of the new housing stock in each local authority area. As discussed in Section 6.2, the total number of replacements across Scotland remains the same across all five lifetime scenarios, it is the peak year which changes. As such Figure 6.3 shows the total number of replacements (for all scenarios) for each local authority in Scotland. Glasgow City Council and City of Edinburgh, shown in red, had the two highest numbers of replacements of 59,822 and 53,359 respectively (Figure 6.3), accounting for 21% of total replacements across Scotland. Fife and South Lanarkshire, shown in orange, also had high numbers of replacements, 36,995 and 36,870 respectively. Shetland (2826), Orkney (2,976), and Na h-Eileanan Siar[21] (3,304) do not have a mains gas grid as discussed in Section 6.3.3. The total number of replacements for each local authority is listed in Appendix 10.7.

Figure 6.4 shows the replacements as a percentage of the total dwellings in each local authority. This is also listed in Appendix 10.7. Midlothian, shown in dark green, has the highest percentage of its total dwellings needing a replacement, 32%. East Dunbartonshire has the lowest with only 15% of dwellings needing a replacement. This reflects the age of the housing stock in each area i.e. Midlothian has a lot of newer houses whereas in East Dunbartonshire

[21] The Western Isles

the majority of homes were built before 1997. These two authorities will face different challenges when it comes to decarbonising heat.

When space and time are combined, a map for each year for each scenario can be created and allows for comparison between each local authority area, as each has a different peak year. For example, in the 15-year scenario, Edinburgh reaches its peak of 5959 replacements in 2034 (Figure 6.5) whereas Glasgow City doesn’t reach its peak of 6530 replacements until 2037 (Figure 6.6). The maps of the Central Belt for every year between 2026 and 2038 for the 15-year scenario are included in Appendix 10.8.

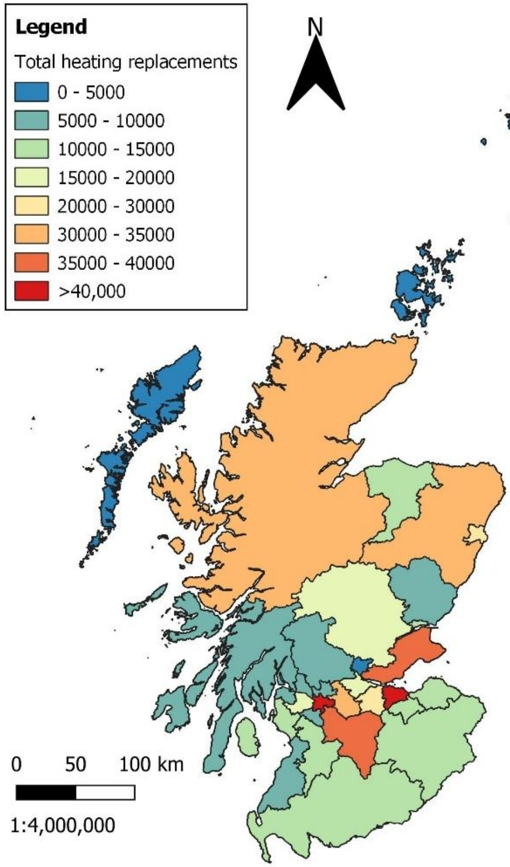

Figure 6.3: Total heating replacements, for all scenarios, for each local authority for houses constructed between 1997 and 2023. The total remains the same regardless of the boiler lifetime scenario. Local authority boundaries from Ordnance Survey (2024a).

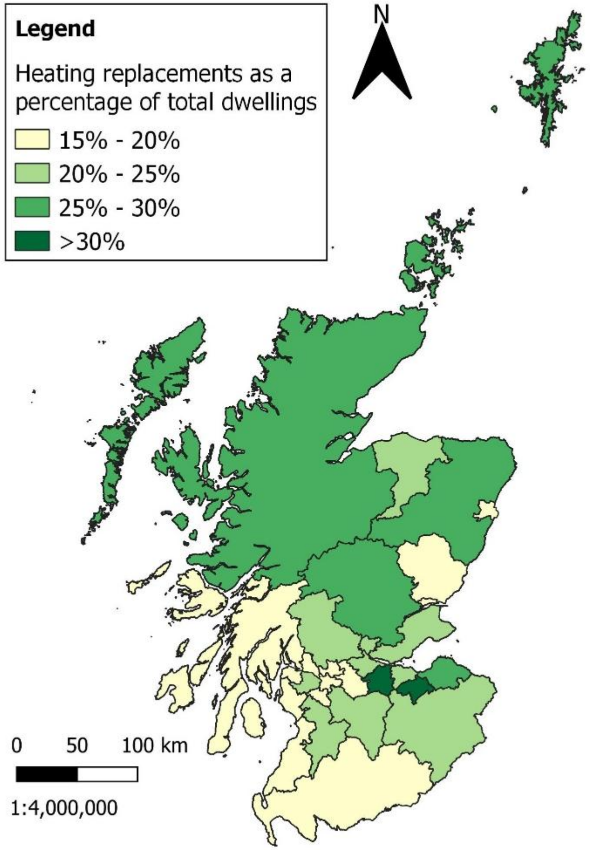

Figure 6.4: Heating replacements for homes built between 1997 and 2023 as a percentage of the total dwellings in each local authority area. Local authority boundaries from Ordnance Survey (2024a).

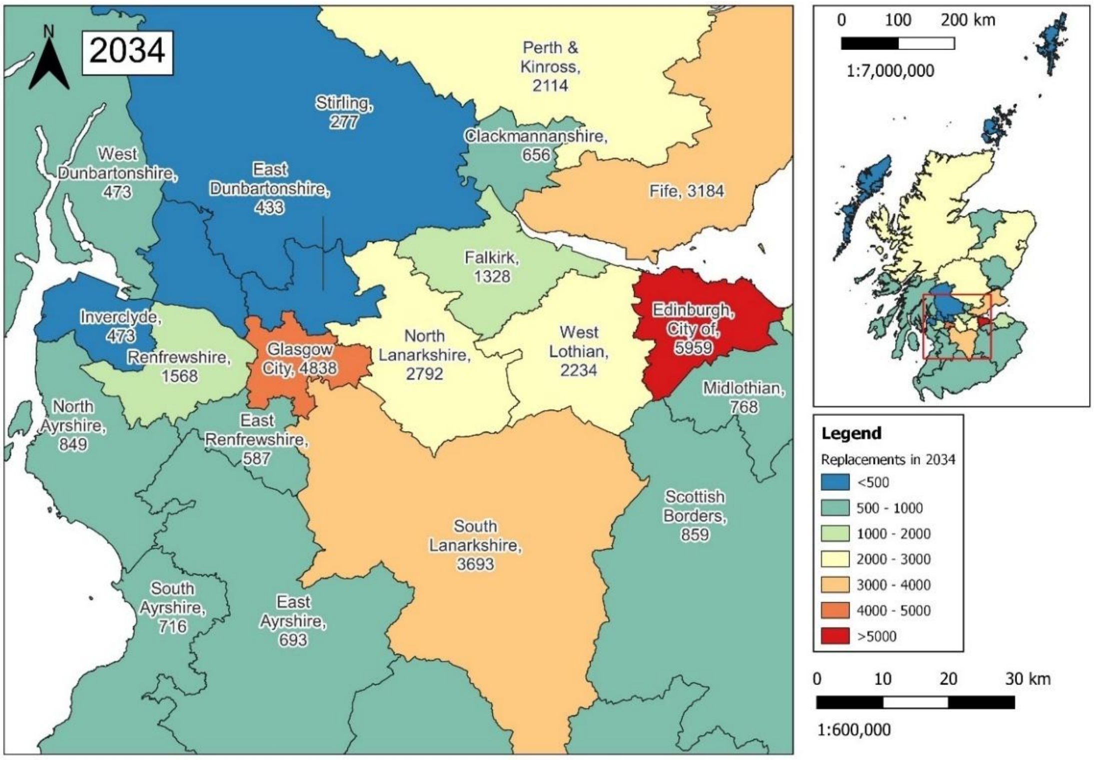

Figure 6.5: Map of replacements in 2034 using a 15-year boiler lifetime for the Central Belt. Contains data from Scottish government (2024e). Local authority boundaries from Ordnance Survey (2024a).

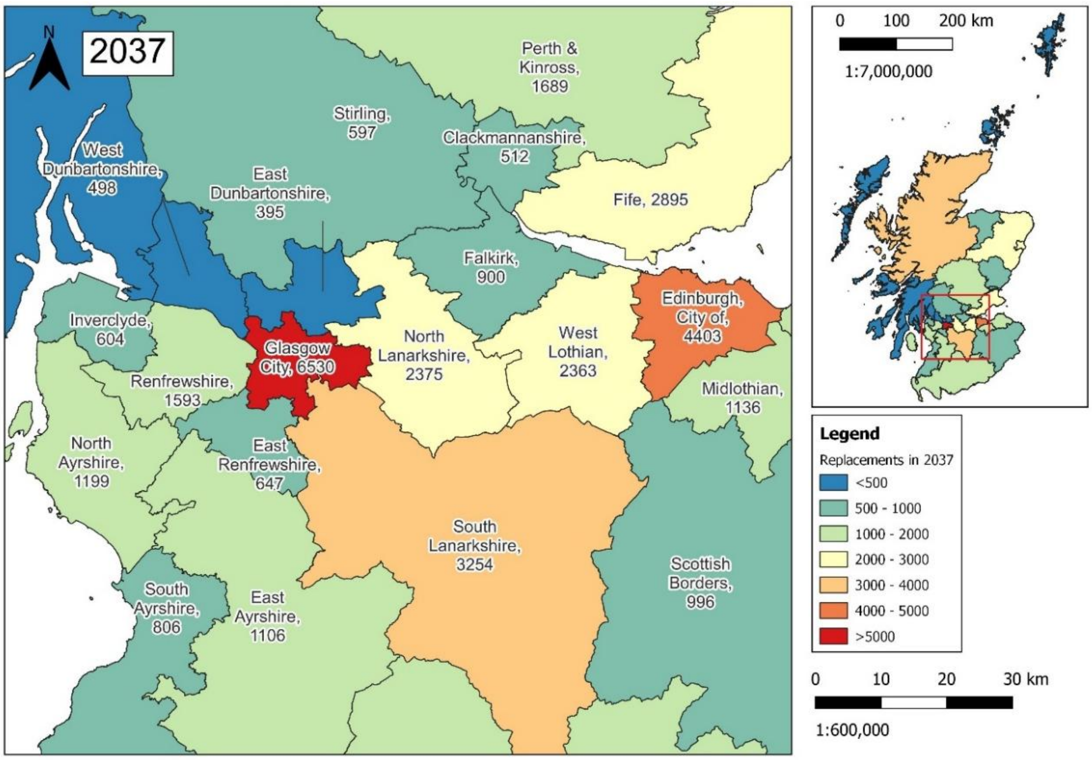

Figure 6.6: Map of replacements in 2037 using a 15-year boiler lifetime for the Central Belt. Contains data from Scottish government (2024e). Local authority boundaries from Ordnance Survey (2024a).

6.3.3 Different heating types

As discussed in Section 2.4.4, the housing stock and heating types is very spatially variable between urban and rural areas in Scotland (Figure 2.19). This method assumes that all heating replacements will be replacing a gas boiler. Whilst it is true that is most homes in Scotland are using a boiler of some kind[22] for heating (88%, Figure 2.20), 12% of homes use alternative methods such as storage heaters (5.8%, Figure 2.20). These alternative heating systems will require a different approach to decarbonisation. So being able to differentiate between different heating system replacements will be important in certain regions.

The Scottish Census (2022) collects data on what type of heating homes in each local authority area are using. The heating types are classified into four categories: mains gas, oil, electric, and other heating system[23]. (‘Other heating system’ includes biomass and solid fuel (e.g. coal, wood, peat) and ‘Electric’ includes direct electric (inc. storage heaters) and heat pumps). Using these data the results from the initial analysis can be adjusted to reflect the current heating systems being used across Scotland. At a local authority level, the percentage of homes using mains gas ranges from 89% in East Dunbartonshire to <1% in Orkney and Shetland (Scotland’s Census, 2022). Mains gas is more prevalent in the Central Belt of Scotland and less common in rural and island locations, where homes are more likely to be ‘off grid’ (Chapter 2.4.4). As such, homes in rural locations have a more varied mix of heating options and often have high levels of electric heating. For example, Orkney and Shetland have 30% and 42% of homes using electric heating respectively. These rural locations also have a high use of oil boilers (28% and 23% in Orkney and Shetland; Scotland’s Census, 2022; Chapter 2.4.4).

This is shown in Figures 6.7 and 6.8 which show the number of replacements of the different heating systems, and the percentage of the total replacements for each local authority, respectively.

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[22] I.e. a boiler could be fueled by mains gas, oil, biomass, or could be electric.

[23] In the census data, heating systems which fall into ‘other heating system’ each have their own category but for ease of this analysis they have been grouped into one.

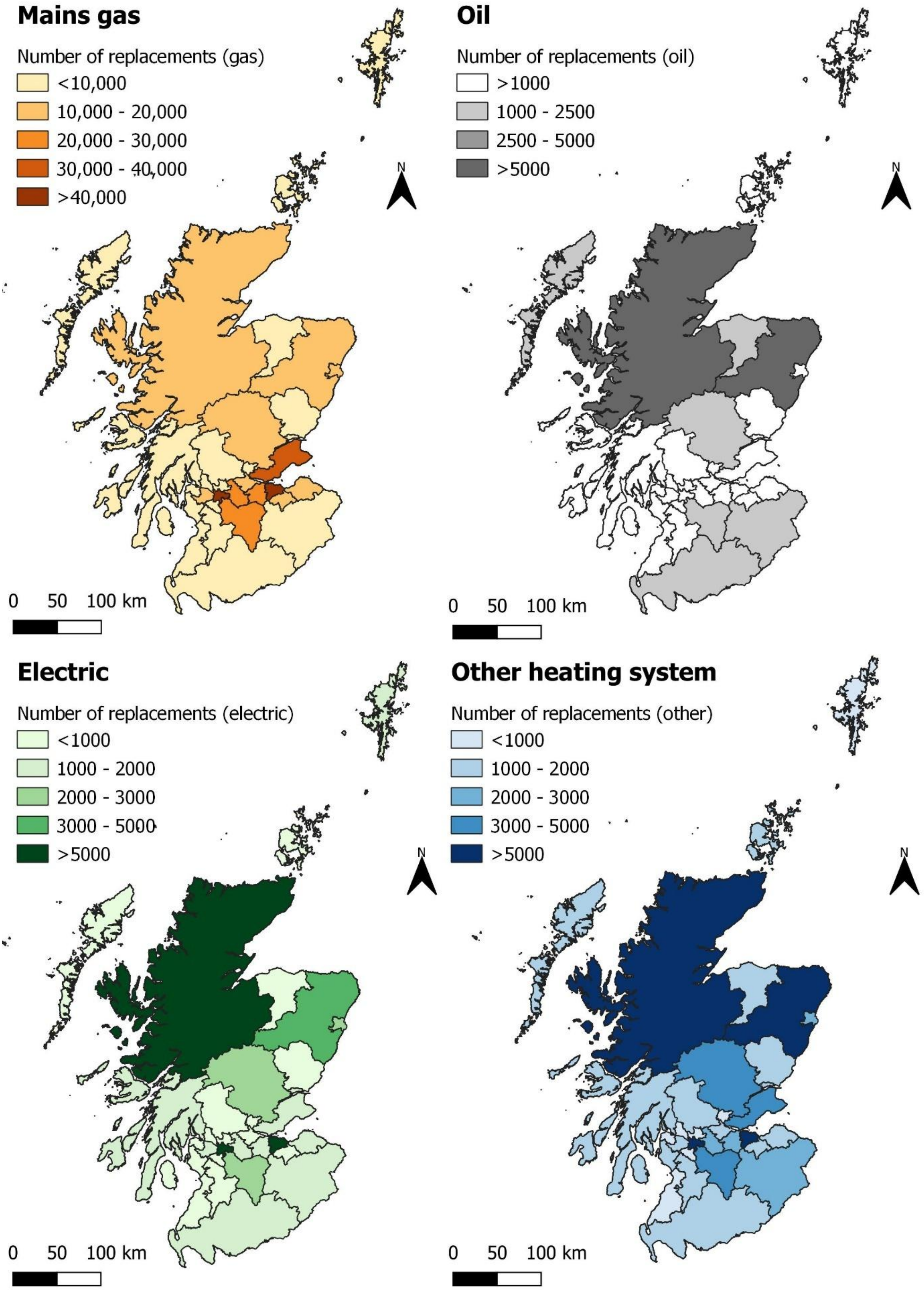

Figure 6.7: Comparison of the number of replacements for each type of heating system in each local authority. Contains data from Scotland's Census (2022) and Ordnance Survey (2024a).

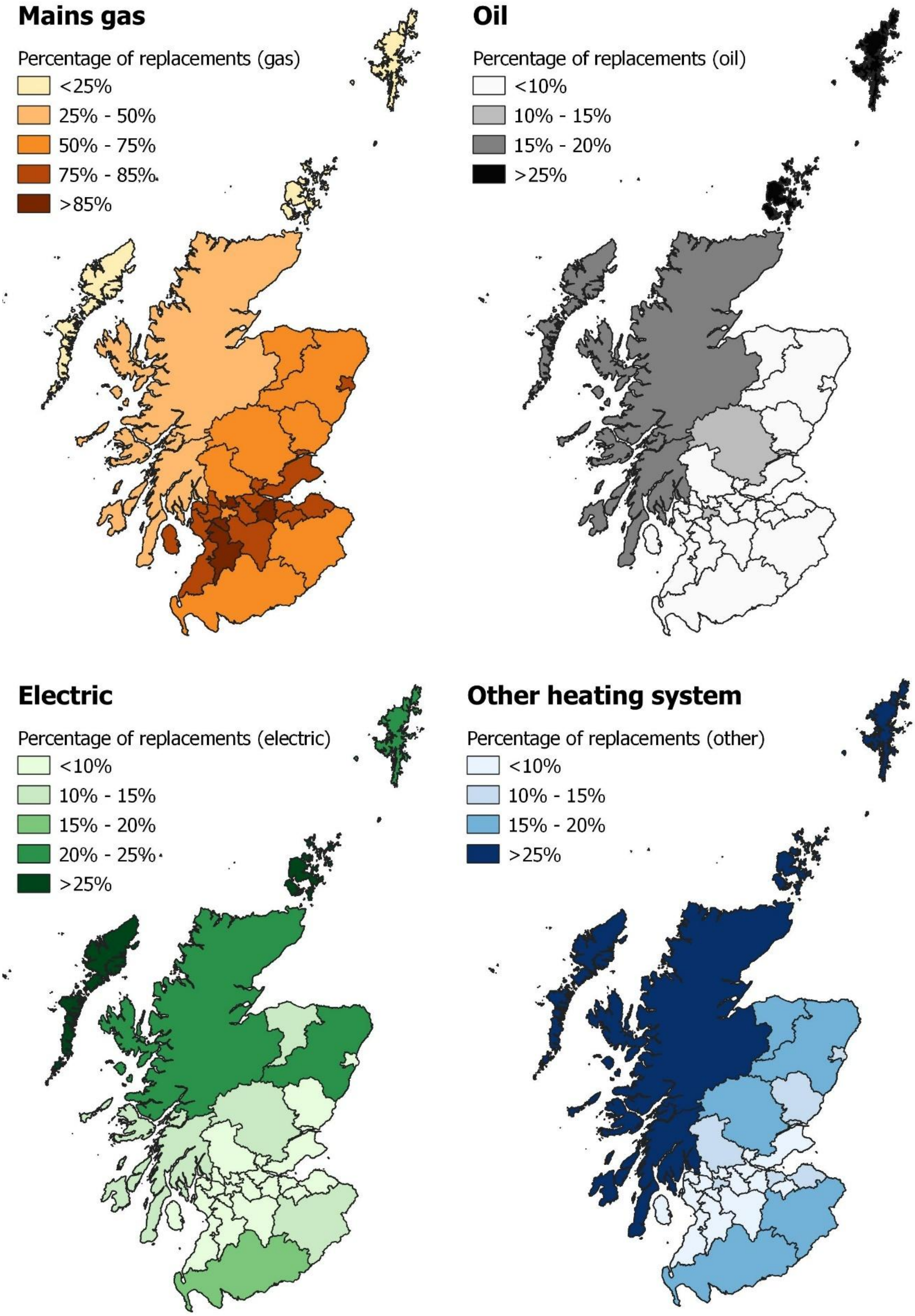

Figure 6.8: Comparison of the percentage of total replacements for each local authority for each of the four types of heating system. Contains data from Scotland's Census (2022) and Ordnance Survey (2024a).

For the following figures, the local authorities have been categorised into seven regions: Cities, Central Belt, Central East, Northeast Scotland, Southern Scotland, Highlands, Islands (Appendix 10.9). The regions are presented with the most urban LAs (cities) on the left of the graphs to most rural on the right (highlands and islands). Within the categories, the local authorities are sorted alphabetically.

For each local authority, Figure 6.9A shows the number of replacements for each type of heating system and Figure 6.9B shows the percentage of total replacements, to allow for a direct comparison between different local authorities. Urban authorities have the highest proportion of mains gas, and that the more rural an authority is, the fewer domestic mains gas connections it has. The more rural locations such as the Highlands and Islands have a higher proportion of oil boilers, whereas the city and Central Belt authorities have a high proportion of gas boilers and practically no oil boiler replacements[24].

[24] Please note that this analysis assumes that the lifetime of all heating systems is the same for each scenario e.g. not different between gas boilers and oil boilers in 15-year scenario.

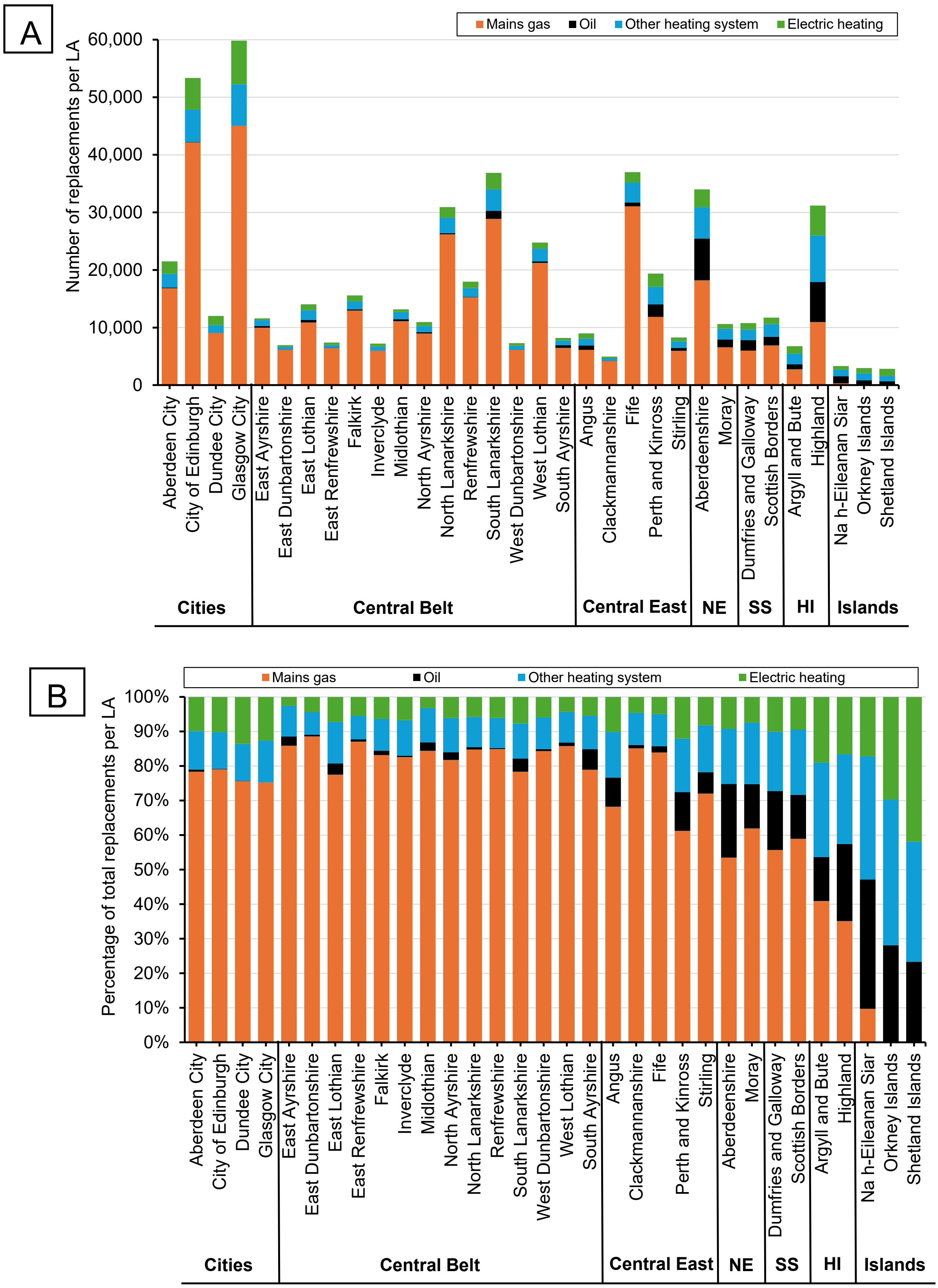

Figure 6.9: A) Number of replacements for each heating type per LA. B) Percentage of total replacements for each LA. local authorities (LA) sorted by region. NE = North east Scotland, SS = Southern Scotland, HI = Highlands.

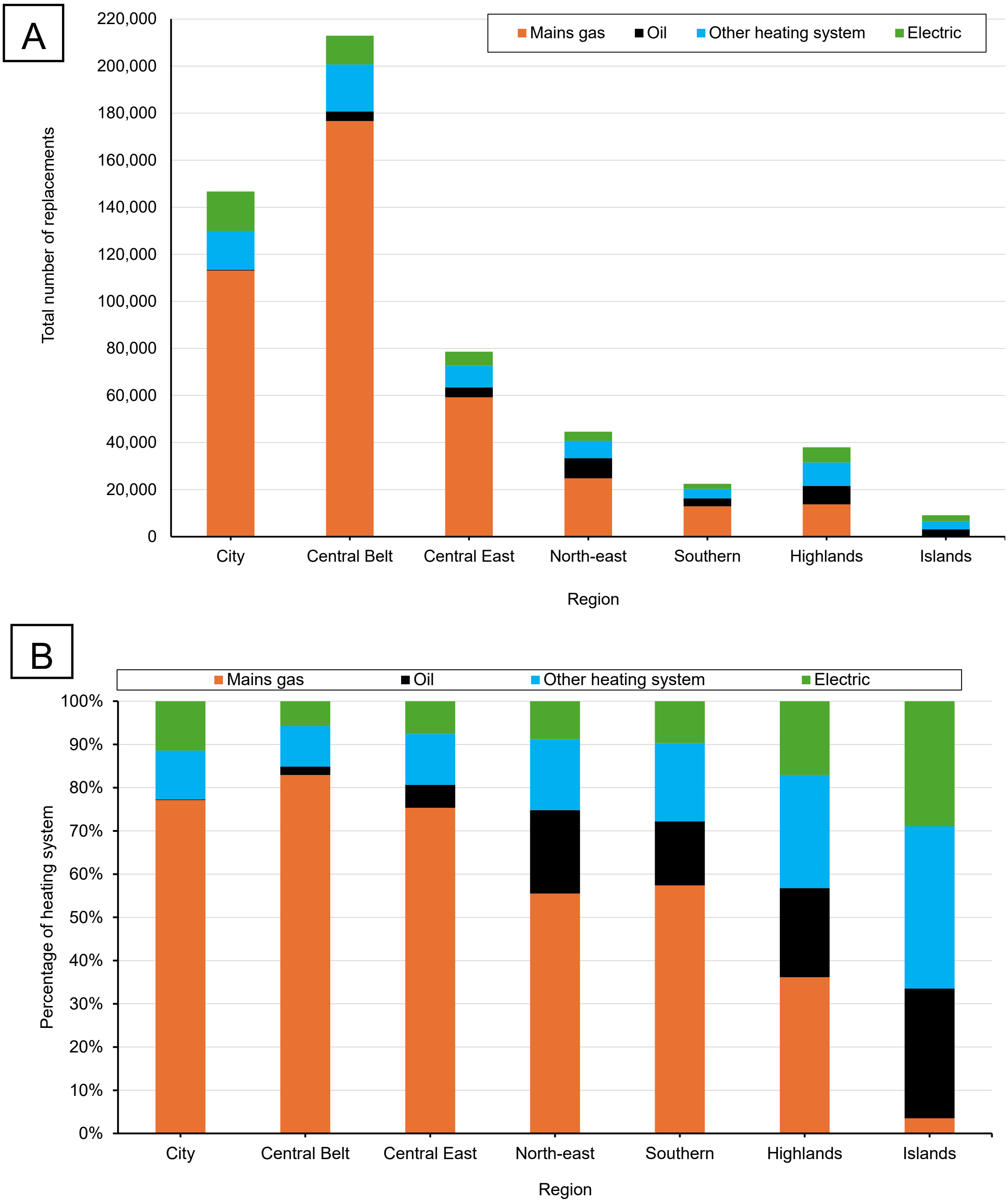

Figure 6.10: A) Number of replacements for each heating type per region. B) Percentage of total replacements for each region.

6.4 Discussion

Throughout the time period of the analysis there is a fairly constant replacement demand nationally, but the demand is variable in location (Figure 6.3), and not all areas have a consistent increase year on year. Different locations reach their peaks in different years. People in Scotland who have already switched to a heat pump have reported finding it hard to find people to maintain or repair their heat pumps (Chapter 3). This analysis shows that there will be a steady demand for heat pump installations or district heating networks over the coming decades but also a steady demand for maintenance, i.e. the heat pumps that have already been installed or will be installed, will need maintaining and will need replaced at the end of their lifetimes. This should give installers (e.g. gas fitters) confidence to retrain from gas boiler maintenance to heat pump maintenance. This information could be useful for local authorities to plan and predict when they may have a surge in demand for new heating systems, and it could also help them plan where a heat network may be best received (for example in a housing estate that was built in 2015, would need the boilers replaced in 2030, and could be a good location for a heat network).

The main limitation of this method is that dwellings built between 1997 and 2023 only account for 22% of the total housing stock in Scotland, so this analysis cannot give a complete picture of future heating demand. Also, the location of these dwellings within each local authority area is unknown. This method does not consider commercial or industrial heat demand which will play a significant role in any future district heating networks as anchor loads and heat sources. These data will have different implications for different stakeholder groups in the effort to decarbonise, which will be discussed in the following sections.

6.4.1 Domestic heat customers

Very few homeowners replace a gas boiler unless they must, as shown in a survey of over 2000 people, carried out by Ipsos MORI and Energy Saving Trust (2013). Most people (70%) replace their heating system either because it has broken down (30%), because the system was coming to the end of its life (31%), or it had become ineffective at heating the home (9%; Table 6.1; Ipsos MORI and Energy Saving Trust 2013). This shows that the majority of people have not planned to switch their boiler but they have been forced to in an emergency situation (i.e. they are without heating and hot water). It is likely that most people in this scenario would be keen to get their home warm again, especially in winter and would opt for the cheapest and easiest solution, which is to replace like for like. Thus, locking them into using gas for another 15 years.

Only 1% of respondents (Table 6.1) replaced their heating system due to environmental concerns, the same amount of people who changed it for aesthetic reasons (Ipsos MORI and

Energy Saving Trust 2013). This shows that the environmental or decarbonisation argument for replacement is just not strong enough for most people. These data were collected in 2012, so that percentage may be higher now due to the increased awareness of the climate crisis, however it is still likely to be relatively low.

Table 6.1: Reasons respondents to a survey gave for replacing heating system in the past. The main categories are given in bold and the reasons within each category are given in italics. Data are from Figure 21 in Ipsos MORI and Energy Saving Trust, 2013 (p.39). n = 2,848.

Reason	Percentage of participants
Broken down/near the end of its life	**61%**
System breakdown	*30%*
Told it would not much last much longer	*14%*
Needed repairs too often	*14%*
Told parts would no longer be available in the future	*3%*
Not working properly/ ineffective	**9%**
No longer heated home adequately	*5%*
Did not heat home/ hot water quickly enough	*3%*
Concerned that it was no longer safe to run	*1%*
Part of a wider property renovation	**13%**
Cost	**4%**
High heating bills with previous system	*2%*
Servicing/repairing the system became too expensive	*1%*
Took advantage of a financial incentive to replace	*1%*
Difficult to use	**1%**
Other	**10%**
Not environmentally friendly enough	*1%*
Took up too much space	*1%*
Didn't like the look of it/ not in keeping with style of home	*1%*
Other	*7%*
Don't know	**3%**

6.4.2 Companies, jobs, manufacturing

Karpathy *et al.* (2022) found that to meet Scottish Government climate change targets, over 16,000[25] installers of electrified heating technologies would be required before 2030. However current estimates are at national level and are not broken down to local authority level.

[25] This maximum number comes from summing the maximum of the three installer categories investigated by Karpathy *et al.* (2022): Heat pump installers: 4600 – 11,400, heat network installers: 320 – 4000, and direct electric installers: 530 – 1100. They also estimate that 4500 and 5400 installers of thermal insulation will be required.

Scotland's local authorities are highly variable in geography, population, and housing stock, ranging from urban to remote rural (Scottish Government, 2020d) and different areas will need different heating solutions, and therefore different heating installers. Furthermore, a survey by Jindal *et al.* (2024) showed that the heat installation industry is dominated by small businesses[26] and that the majority of businesses (87%) wanted to install more heat pumps but faced several barriers, such as a lack of customer demand or increased administrative tasks for heat pump installation (Jindal *et al.*, 2024). As such these may require incentives or additional support to become more mobile and expand their business. This analysis shows that there will be a steady pipeline of future electrified heat installation and maintenance jobs in Scotland, as well as manufacturing of heat pumps, and for planning and construction of heat networks. This should also give companies confidence to retrain into heat pump installation and perhaps show the government they need to provide further support to heat pump installers.

6.4.3 Local authorities

Having an awareness of where entire housing estates are likely to require a new heating system could allow local authorities to better plan the location of district heating networks, which require a certain number of dwellings to join to make it worthwhile financially. It also compliments LHEES could help to plan retrofit upgrades: for example, if the authority knows that in seven years those houses will need new heating, they can start working on the energy efficiency of those buildings in advance to ensure optimal efficiency of the new heating systems. It could also allow inter-authority collaboration on heat network construction or sharing heat pump installers, they could work across a region to meet demand at different times in different locations. This will be explored further in Chapter 7.

6.4.4 National government

Currently the cost of electricity is the highest operational cost for ambient heat sources such as minewater thermal (Chapter 3). In recent years, electricity prices in the UK have been around four times greater[27] than gas prices (Sarsentis and Orso, 2023). Currently there are a number of levies placed on consumer electricity and gas bills to raise money for the government for schemes such as the Renewables Obligation and Feed in Tariffs. Currently the levies placed on electricity prices are three times higher than those on gas, making up 16% of the final price of electricity and only 5.5% of the final price of gas (Kavan, 2025a). Shepheard *et al.* (2025) state that *"reforming levies on electricity and gas bills is a must-do*

[26] In the survey caried out by Jindal *et al.* (2024), 19% of respondents were sole traders, and 54% owned a business with five or less employees (pg.19).
[27] Between 2011 and 2021, the UK had an average electricity to gas ratio of 3.8, and between 2018 and 2022 this ratio was 4.4 on average. (Sarsentis and Orso, 2023)

action to reach net zero" (p.4). Shifting the levies from electricity bills onto gas bills or general taxation could reduce energy bills for 8 million households by making electric heating, like heat pumps, cheaper to run (Shepheard *et al.*, 2025, Kavan, 2025b). The levy reforms suggested by Shepeard *et al.* (2024b) could make running a heat pump £400 per year cheaper than using a gas boiler. By making heat pumps cheaper to run this could increase heat pump uptake by 60% (Shepheard *et al.*, 2025). They would also reduce bills for households using direct electric heating, who often are experiencing acute fuel poverty (Section 2.4.4.3). For the UK government, the benefits of moving the levies include making the Boiler Upgrade Scheme (BUS) more cost effective (£7500 grant for households to install heat pumps). This scheme is currently affordable for the government, due to the low uptake of heat pumps, but it will become much more expensive for the government as demand for heat pumps rises (Shepheard *et al.,* 2025).

6.5 Conclusion

In conclusion, the method presented in this Chapter provides high-level estimates for the number of homes which may need a replacement heating system in the next 20 years. This could be helpful for local authority planning, electricity companies planning grid upgrades, or small business deciding whether to retrain their staff.

7. CHAPTER 7: Synthesis

Minewater is an appealing prospect for decarbonising heat in ex-mining communities. Reusing legacy infrastructure that would otherwise be an environmental liability has public appeal and is often quoted as a main reason for using minewater (Dickie *et al.*, 2020, Roberts *et al.*, 2023). However, there are many technical, economic, and social challenges that come with this technology, and if it is not the most optimal heat solution for a given location, then it should not be pursued in that location (as with any heat technologies). The competitiveness of minewater thermal with other sources of ambient heat in a location should always be considered.

This thesis aimed to assess and quantify if Scotland's minewater thermal resources could contribute to the decarbonisation of heat using spatial analysis. Each of the preceding four chapters, either already published, or in preparation for publication, had their own discussions, so this synthesis chapter aims to bring together themes from those four discussions. Chapter 3 explored the barriers and enablers to the development of minewater in Scotland in the context of three topic areas, resource, cost and people. Chapter 4 provided a high-level estimate for the amount of energy or storage for a range of technologies that could be achieved given certain criteria and applies the resource vs. reserve concept to mine shafts. Chapter 5 tested three different methods for estimating the volume of mined out voids on four collieries and for Scotland as a whole. Chapter 6 used house building statistics to estimate how many heating systems may need to be replaced in each local authority in the coming years. In this discussion I will attempt to integrate the findings from these chapters to assess whether Scotland could use its abandoned mines for heat decarbonisation, and if so when and where?

Chapter 3 explored advantages and disadvantages of minewater thermal from the perspective of industry experts. The participants in this study felt that the key advantage of minewater thermal resources was its potential for thermal storage. This ability for storage is what differentiates it from other sources of low carbon ambient heat, such as rivers or sewers. Other advantages included a perceived co-location with heat demand and the existence of skills in Scotland to carry out these projects. Numerous barriers to minewater thermal resources were also raised in Chapter 3, the main one being that of cost, both upfront and operational (Table 3.4). There were a range of other disadvantages discussed such as feasibility risks, regulation issues, low heat capacity (relative to other heat sources, and hence the attraction of also using the minewater for storage), lack of heat demand, lack of job creation, and the fact that other heat sources may be more viable, cheaper and easier to implement. Chapter 3 also called for a hierarchy of low carbon heat sources, one that takes advantages of the different heat sources in a geographical area.

Chapters 4 and 5 raise a major barrier that was not discussed by interviewees in Chapter 3, that of data quality. In these chapters, the analysis shows that the quality of the publicly available data was not detailed enough to make reliable high-level estimates of minewater resources at a national level, for either mine shafts or underground mine workings. Having high quality high-level estimates could help to increase the confidence in this technology which was raised as important aspect for development by stakeholders in Chapter 3. The data have several limitations making assessing abandoned mines for thermal reuse more difficult. Firstly, the data within the datasets are quite sparse, for example, in the mine shaft entries database less than a third of the data points have a shaft depth, and only 3% have a measured diameter. Information on shaft construction, lining material and backfill status are all missing from the publicly available data. Similarly, the underground workings dataset is incomplete with 16% of panels in the data being unattributed to a specific colliery (labelled as 'unnamed'), making individual colliery volume estimations difficult. This makes a standardised approach to estimating volume at a national or regional scale difficult, meaning that potentially viable thermal resources will be missed and less optimal collieries may be pursued. This means that it is difficult for researchers, government or developers to take a strategic approach to using minewater resources. The uncertainty of the data on condition and size of mines, presents a large risk for developers and investors (both public and private), as they will need a lot of money to reduce the uncertainty (for ground investigation, modelling etc.). Especially when high interest rates mean there is low appetite to invest (Bank of England, 2025).

The data on housing used in Chapter 6 is more reliable, at least for houses built since 1997, but the method presented in Chapter 6 has other limitations. It is useful for letting local authorities know where and when they could best target a new district heating network, or electricity grid upgrade planning.

7.1 Heat in place calculations

As discussed in Chapter 5, there have been a few high-level estimates of the amount of heat that could be provided from coal mines in the UK (Adams and Gluyas, 2017) or Scotland (Gillespie *et al.*, 2013, Todd *et al.* (2019). Here those estimates and their assumptions will be interrogated and compared with heat in place calculations based on the volume estimation calculations in Chapter 5. Estimates for heat are always presented in different units, so for this analysis they will be all be converted to megawatt hours (MWh). Table 7.1 compares the three estimates.

Adams and Gluyas (2017) estimated that 38,500 TJ of heat energy could be extracted from the void left by the 15 billion tons mined from UK coal mines, enough to heat 650,000 homes, which works out at about 16,400 kWh per home. This is higher than OFGEM's figure for typical annual gas usage in a medium sized home of 11,500 kWh, and higher than the oft quoted figure of 10,000 kWh of energy consumption per household per year but makes for a conservative estimate of the number of houses. If it is assumed that on average Scotland accounted for 11% of total UK coal production (Section 5.5.3), 11% of 38,500 TJ (10.7 million MWh) is 1,177,330 MWh. Based on an average heat demand of 16,400 kWh per home (per year), this could heat about 71,788 homes (approx. 2.8% of the homes in Scotland[28], Table 7.1).

Todd *et al.* (2019) estimated the annual amount of geothermal energy available in the Midland Valley of Scotland based on a geothermal flux of 65 mW m^{-2} and a mined-out area of 4800 km^3 (from Gillespie *et al.*, 2013) would be 9.88 $x10^9$ MJ (2724 GWh), which Todd *et al.* (2019) state is 8% of Scotland's domestic heat demand. Based on the above heat demand per home, 2724 GWh is enough to provide heat for between 166,122 and 272,440 homes between 6.5% and– 10.7% of Scottish homes (Table 7.1).

Gillespie *et al.* (2013) estimated that one third of Scotland's heat demand could be provided by minewater, from an estimated flow rate of 60 l s^{-1} km^{-2} to give an average of 2.5 MW km^{-1} in the mined areas of Scotland. Multiplied by the mined area, which they take to be 4800 km^3, gives 12,000 MW. Their method is unclear, by finding the heat usage rate of domestic heat, which they take to be 33GW[29], based on an estimated value for Scottish heat demand in 2020 (this report was written in 2013), which was 60.1 TWh and a usage time of 1800 hours a year. 12,000 MW is. Given their estimate of 12,000 MW and 1800 hours a year, this gives a total heat resource of 21.6 million MWh (21,600 GWh) in Scotland's mines, 35% of their predicted

[28] 2.5 million homes in Scotland
[29] 12,000 MWh (12 GW) is approximately one third of 33 GW)

heat demand. 21,600 GWh could provide heat for between 1.31 million and 2.16 million homes (Table 7.1), between 52% and 85% of all the homes in Scotland[28].

Table 7.1: Heat estimates for Scotland's mines from the literature and the number of homes they could provide heat for.

	Estimate	Method used	Estimate in MWh	Number of homes		Proportion of Scottish homes [28]
				10,000 kWh a^{-1}	16,400 kWh a^{-1}	
UK	Adams and Gluyas (2017)	Total UK coal output as a proxy for volume	10,703,000 (UK) 1,177,330 (Scotland = 11%)	117,733	71,788	2.8 – 4.6%
SCOTLAND	Todd *et al.* (2019)	Geothermal flux and mined area	2,724,000	272,440	166,122	6.5 – 10.7%
	Gillespie *et al.* (2013)	Flow rate, heat per km^2, and mined area	21,600,000	2,160,000	1,317,073	52 – 85%

In Section 5.5.2, two methods were used to calculate a mined-out volume for the whole of Scotland. Here these data are used to calculate heat in place (Table 7.2) to provide an estimate of the number of homes that could be heated (Table 7.3). These calculations assume that due to void collapse, only 25% of the mined volume remains (Adams and Gluyas, 2017, Andrews and Shipton, 2021).

Heat in place (for heat extraction and thermal storage) can be calculated using this equation:

$$H = [\rho_w C_p] \cdot V \cdot (\Delta T)$$

where H = heat energy (J), ρ_w = density of water (kg m^{-3}), C_p = specific heat capacity of water (J kg^{-1} K^{-1}), V = volume of aquifer, or in this case mine shaft (m^3), ΔT = temperature change (Adapted from Downing and Gray 1986). This equation gives the heat energy in joules which is then converted to MWh (Section 4.2).

A range of temperature changes (ΔT) will be calculated for each colliery; 1, 2, 5, and 10 degrees (Table 7.2). These calculations give a range of between 5,129 and 276,943 houses that could be heated by minewater across Scotland (Table 7.3). As discussed in Chapter 5, the estimate from Method 1, which used the MRA underground working dataset, is likely a significant overestimate of the 'true' volume (Section 5.5.3). When this uncertainty is taken through into the heat in place estimates, the number of houses that could be heated will also be overestimated. The estimate of heat from Method 1 (2,769,427 MWh, Table 7.2) is very similar to the estimate from Todd *et al.* (2019) of 2,724,000 MWh which is also based on mined-out area (derived by Gillespie *et al.* (2013) based on the total area of all the panels in the MRA database). Both Method 1 and Todd *et al.* (2019) estimated between 6% and 11% of Scottish homes being heated by minewater resources.

When the volume estimates calculated using Method 3, which used historical coal output data, are used, there is a range of 5,129 to 84,119 homes that could be heated, between 0.2% and 3.2% of all the occupied dwellings in Scotland[30]. This is approximately 15% of the homes needing a heating replacement in Chapter 6[31]. Of course, this heat could only be used in coalfield areas, as heat cannot travel far. This value is closer to that from Adams and Gluyas (2017), which is also based on historical coal output data and they also both estimate between 2 and 5% of Scottish homes. These estimates represent a large volume that could be used as thermal storage, this will be explored further in Section 7.3.

Table 7.2: Heat in place for the two whole-of-Scotland estimates in Chapter 5. Method 1 used the MRA underground workings dataset (MRA, 2024c). Method 3 used historical coal output data from Oglethorpe (2006) to calculate volume.

Method	Volume	25% of volume	Heat in place in MWh based on different change in temperature (ΔT)			
			1°C	2°C	5°C	10°C
Method 1	3,798,070,968	949,517,742	276,943	553,885	1,384,713	2,769,427
Method 3	1,153,626,396	288,406,599	84,199	168,237	420,593	841,186

Table 7.3: Estimates for the number of houses that could be heated for each of whole-of-Scotland estimate in Chapter 5. The percentage of houses is based on a total number of occupied dwellings in Scotland of 2.55 million (Scottish Government, 2024b)

Method	Number of houses				Percent of Scottish homes
	Minimum (ΔT = 1°C)		Maximum (ΔT = 10°C)		
	10,000 kWh a^{-1}	16,400 kWh a^{-1}	10,000 kWh a^{-1}	16,400 kWh a^{-1}	
Method 1	27,694	16,887	276,943	168,867	6.6 – 10.8%
Method 3	8,412	5,129	84,119	51,292	2.0 – 3.2%

7.1.1 Individual collieries

From Chapter 5, the method that most accurately recreates the abandonment plans was Method 2 (individual digitisation of abandonment plans). Abandonment plans are the closest thing we have to knowing what is in the subsurface, therefore the volume estimates from this method will be used in the calculations for the individual collieries. As before, 25% of the volume calculated by Method 2 in will be used to calculate in heat in place (Table 7.4) for a range of temperature changes (ΔT).

[30] 2,550,000 occupied dwellings in Scotland (Scottish Government, 2024c)
[31] 552,421 replacements (Chapter 6)

Table 7.4: Heat in place for the four collieries in Chapter 5.						
Colliery	Method 2 volume	25% of M2 volume	Heat in place in MWh based on different change in temperature (ΔT)			
			1°C	2°C	5°C	10°C
Seaforth	1,059,383	264,846	309	618	1,545	3,090
Cardowan	12,455,362	3,113,841	3,633	7,266	18,164	36,328
Barony	26,690,444	6,672,611	7,785	15,569	38,924	77,847
Killoch	16,863,798	4,215,950	4,919	9,837	24,593	49,186

Table 7.5: Estimates for the number of houses that could be heated for each of the four collieries in Chapter 5. N.b. 10,000 kWh = 10 MWh						
Colliery	Minimum heat in place MWh (ΔT = 1°C)	Maximum heat in place MWh (ΔT = 10°C)	Number of houses			
			Minimum (ΔT = 1°C)		Maximum (ΔT = 10°C)	
			10,000 kWh a^{-1}	16,400 kWh a^{-1}	10,000 kWh a^{-1}	16,400 kWh a^{-1}
Seaforth	309	3,090	31	19	463	283
Cardowan	3,633	36,328	363	222	5,449	3,323
Barony	7,785	77,847	778	475	11,677	7,120
Killoch	4,919	49,186	492	300	7,378	4,499

Barony Colliery had a minimum heat in place of 7785 MWh based on a temperature change of 1°C (Table 7.4), which if it were used for heat extraction, could provide heat for between 475 and 778 homes (Table 7.5). The nearest settlement to Barony colliery is the village of Auchinleck, around 2 km to the east, and has a population of 3,630 (NRS, 2022). If the average household size for East Ayrshire is taken to be 2.12 people per household (NRS, 2025), then the number of households in Auchinleck is approximately 1712. Based on the low heat in place estimate (ΔT = 1°C) Barony's minewater resource could heat between 28% and 45% of the homes in Auchinleck. However if the ΔT was 10°C, then heat in place for Barony would be 77,847 MWh (Table 7.4), which could provide heat for between 7,120 and 11,677 homes (Table 7.5). This maximum estimate would be enough to provide heat for the whole of Auchinleck, the neighbouring town of Cumnock (approx. 4100 homes[32]) and the nearby village of Ochiltree some 3 km west of Barony (approx. 490 homes[33]) and still have heat left over. In fact, this maximum estimate would be more than the heating replacement demand for the whole of East Ayrshire determined in Chapter 6 of 11,603 replacements (Appendix 10.7).

[32] Cumnock has a population of 8,700 (NRS, 2022).
[33] Ochiltree has a population of 1040 (NRS, 2022).

The wide range of estimates for heat in place varies from less than a third of a small village to heating an entire region[34], reveals the unreliability of high-level estimates for assessing the potential of minewater thermal resources for heat decarbonisation. All these calculations rely heavily on a number of parameters and assumptions that will be highly spatially variable. There is no way of verifying these without more detailed modelling and ground investigation or geophysical techniques, such as the amount of void which that has collapsed, the degree to which mine workings have flooded, the recharge rate, or the geochemistry of the water. These uncertainties have significant impacts on the ΔT that could be achieved at Barony Colliery, or any other colliery, again pointing to the need for careful site-by-site assessment. If these uncertainties are not carefully considered before selecting a colliery to investigate for thermal reuse, then time, money and resources could be wasted investigating mine resources, which will not be realistic prospects for heat decarbonisation. This will damage the reputation of minewater as a resource among the local public (public trust) and will waste time and money that could have been spent investigating more viable heat sources in that area. This reveals the danger of using high-level estimation to assign value to minewater thermal resources. However, without high level estimates, how will we know which collieries to investigate in more detail?

7.2 Comparison of mine volumes with thermal storage volumes

The mine volumes calculated in Chapter 5 and mine shaft volumes from Chapter 4 can also be compared with the thermal storage volumes collated in Section 2.3.2. Of the 23 thermal stores reviewed in Section 2.3.2 and shown on Figure 7.1 the average volume was 33,152 m^3 (± 51,784 m^3 SD) and the average heat demand was 9,785 MWh per year (± 14,115 MWh SD). Heat in place was calculated for the four mines from Chapter 5 and for the 28 mine shafts (TES with geographic factors) to compare to thermal storage volume against heat demand from Figure 2.8, to create Figure 7.1. Whilst heat in place and heat demand are not the same, it is useful to be able to compare them against known thermal stores.

As above, for the underground mine workings, to account for collapses, 25% of the volume was defined as available void space. For the mine shafts 100% of the volume was used as they are not likely to have collapsed in the same way as underground workings. However, as discussed in Chapter 4 the backfill status of these shafts is unknown and they may have been backfilled to the surface, with varying levels of remaining void space depending on the backfill materials. There is no way of knowing without checking each individual mine shaft.

[34] If the heat could be distributed across the authority area

Figure 7.1 shows that even 25% of the smallest of the four mines investigated in Chapter 5, Seaforth Colliery (264,846 m^3, Table 7.4), has a larger volume than the biggest thermal store, Vojens pit thermal storage (PTES) in Denmark with a storage volume of 200,000 m^3, which at the time of its construction was the largest pit thermal storage scheme in the world (Epp, 2014, State of Green, 2014). The other three collieries, Barony, Killoch, and Cardowan are significantly larger, as they all have (25%) volumes over 1 million metres cubed. This shows the large potential for storage that abandoned coal mines represent. However, unlike the Vojens PTES this volume is not concentrated in a single pit but is distributed across potentially tens of thousands of individual mine panels (e.g. the MRA data show that Killoch had over 20,000 panels, see Appendix 10.6).

The mine shafts presented on Figure 7.1 are the 28 shafts from Section 4.3.2.2 that were within 1 km of a heat source and have a volume of over 1000 m^3 (the minimum size that an inter-seasonal thermal store needs to be to be efficient (Mangold and Deschaintre, 2015)). The largest of these mine shafts has a volume of 38,996 m^3. These mine shafts are more similar to the PTES as they each represent a single column of water which could be used in the same way as a tank thermal storage scheme (TTES), the largest of which is Friedrichshafen TTES in Germany, which has a volume of 12,000 m^3 and serves a heat demand of 1400 MWh per year (Table 2.6).

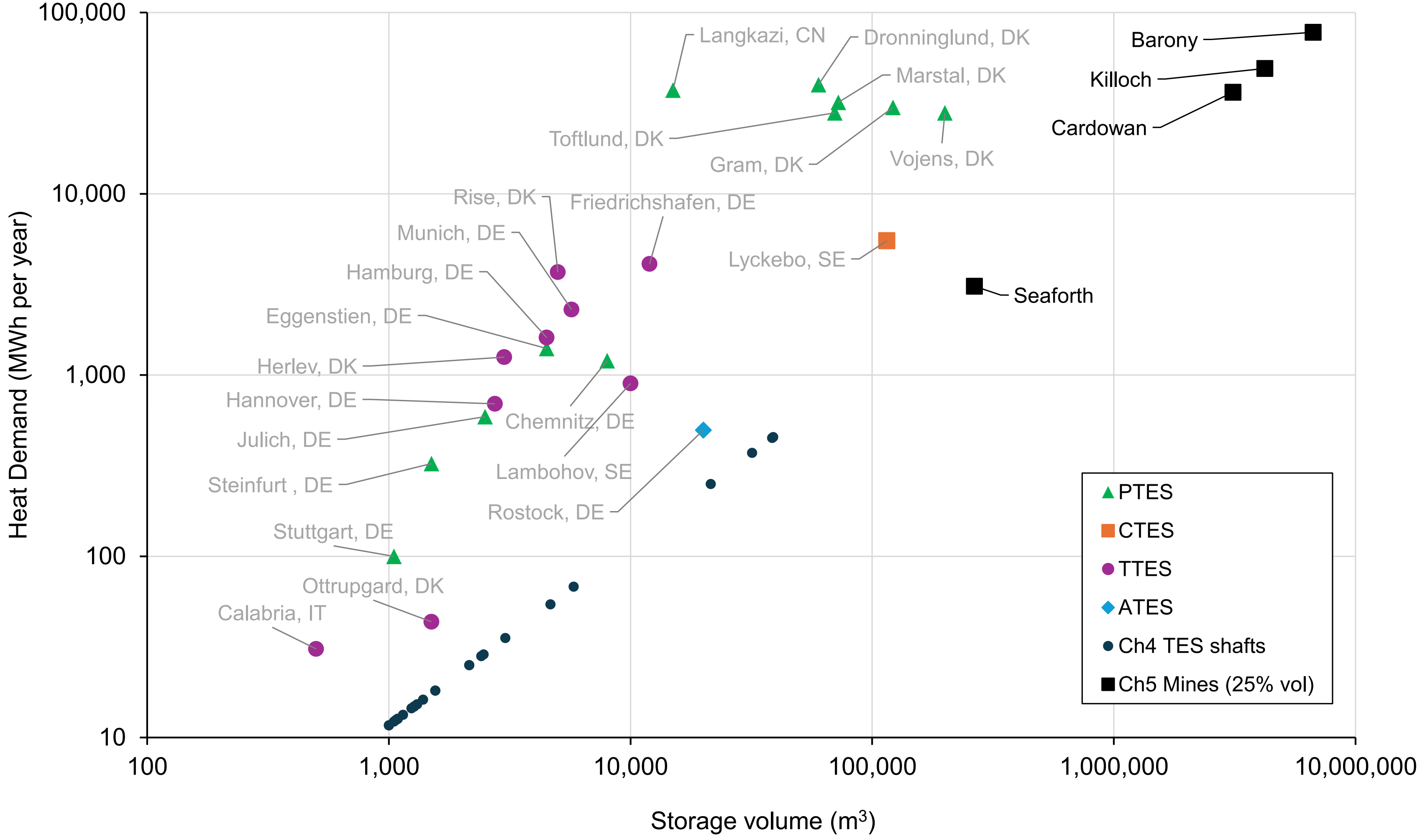

Figure 7.1: Storage volume vs heat demand (Figure 2.8) with mine shafts (Chapter 4) and underground workings (Chapter 5) added. Heat in place calculated using a ΔT of 10°C. Both axes use a logarithmic scale.

7.3 Mine volume per local authority

The Scottish Government is taking a local authority level approach to heat decarbonisation, through its implementation of the Local Heat and Energy Efficiency Strategies (LHEES). It would therefore be useful for those local authorities to know how much potential they have for using minewater thermal resources. As such, the volume of mine shafts and underground mine workings have been collated to a local authority level (Figure 7.2 and Figure 7.3). This can help assess which local authorities should spend more money and time investigating minewater in their area and which ones should pursue other heat decarbonisation options.

7.3.1 Mine shaft volumes

Chapter 4 found that there are 1035 mine shafts in Scotland that met some basic screening criteria for thermal storage (>50 m deep, >1000 m^3, Figure 4.6 and Figure 4.7). The average volume of these shafts was 2802 m^3 ± 3493 m^3 (standard deviation) and the total volume was 2,900,244 m^3. Figure 7.2 shows the spatial distribution of those 1035 shafts across the Central Belt of Scotland (blue circles) and the total mine shaft volume for each local authority area in metres cubed. Sixteen local authorities had mine shafts that met the criteria. The average mine shaft volume per local authority was 179,751 m^3 ± 179,153 m^3 (standard deviation) and ranges from 3078 m^3 from just 2 shafts in East Renfrewshire to 606,642 m^3 across 251 shafts in North Lanarkshire.

7.3.2 Underground working volumes

Using the underground workings dataset (MRA, 2023c) used in Method 1 in Chapter 5, the total volume of mine workings across Scotland was estimated as 3.8 billion m^3 (Section 5.5.2, Table 5.6). The total volume for each local authority area can be calculated. There were 21 local authorities that had some underground coal mine workings within their boundaries. Figure 7.3 shows the extent of the workings and their total volume for each local authority area. The average volume across the 21 local authorities was 180,860,522 m^3 ± 222,172,387 m^3 (standard deviation), the median was 96,268,596 m^3, and the range was 738,477,549 m^3 from a low of 107,610 m^3 in the Scottish Borders to 738,585,158 m^3 in North Lanarkshire.

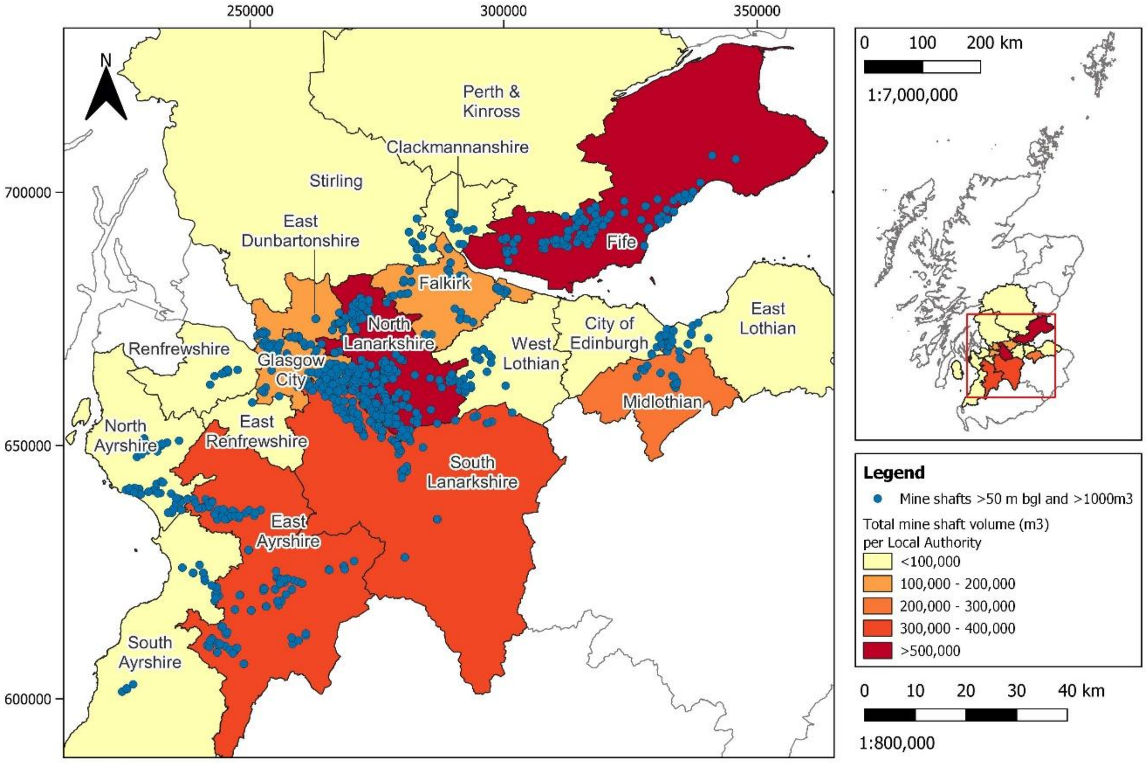

Figure 7.2: Mine shafts and mine shaft volume per local authority. Contains data from MRA (2023e) and Ordnance Survey (2024a).

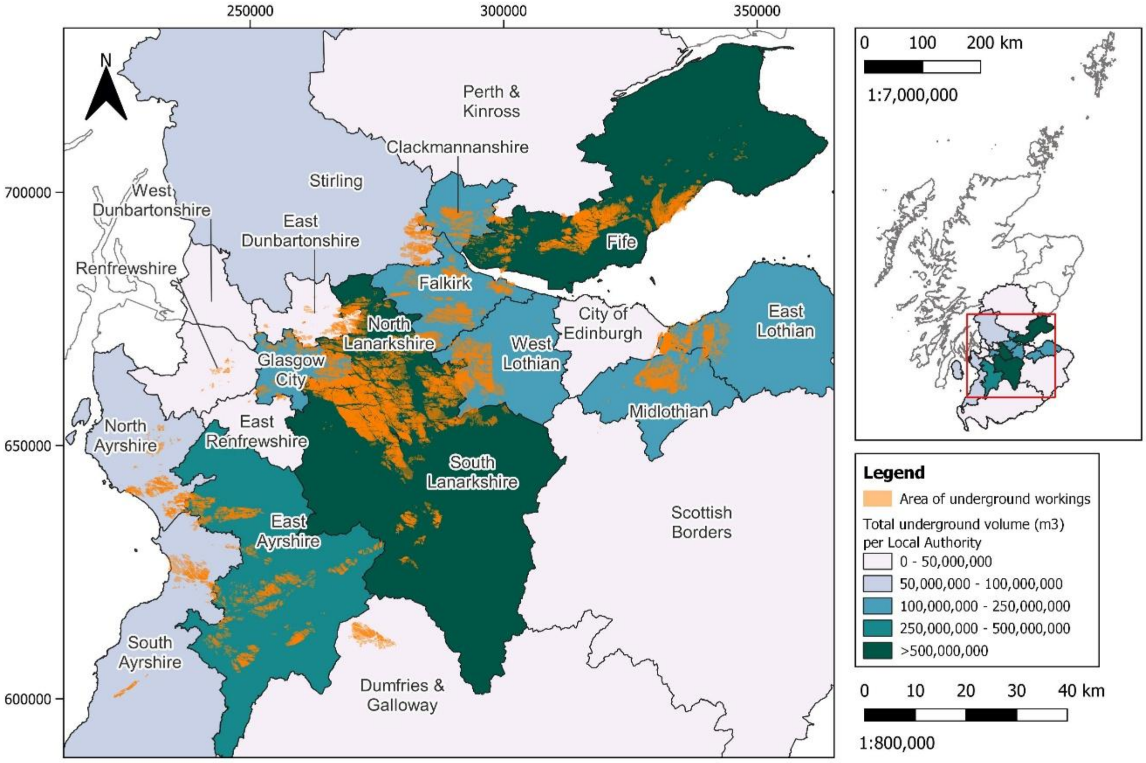

Figure 7.3: Underground mine workings and mined out area volume per local authority. Contains data from MRA (2023c) and Ordnance Survey (2024a).

7.4 Coalfield classification system

Using the volume data from above to determine which local authorities in Scotland have the most opportunity for using minewater thermal resources, local authority areas were classified based on the volume of underground workings in each authority and the area that is underlain by mine workings. As this high-level estimate does not take into account overlapping seams or depth to workings (such as in Walls *et al.*, 2024), or other surface factors (this will be considered in Section 7.5). The classification methodology is included as Appendix 10.10. The final coalfield classifications for 18 authorities[35] are shown in Figure 7.4. Please note that the volume estimates in this section are based on Method 3 from Chapter 5 and use the MRA underground workings dataset (MRA, 2023c), as established in Chapter 5, these data are likely to give a large overestimate of the 'true' volume, therefore these numbers represent an absolute maximum volume. These coalfield classifications will be used in the remainder of this chapter to categories local authorities for analysis. Authorities were classified into large, medium, small and peripheral coalfields, reflecting their potential for thermal storage.

Four local authorities were classified as having a large potential for storage (shown in dark green on Figure 7.4); Fife, North Lanarkshire, South Lanarkshire, and East Ayrshire. These four authorities each have a mined-out volume of over 400 million metres cubed and over 100 km^2 of the local authority is underlain by mine workings. This likely represents a significant enough opportunity for these authorities to benefit from investigating using minewater thermal resources. In the case of North Lanarkshire over half of the local authority area is underlain by coal workings[36]. Four authorities, Falkirk, Glasgow City, Midlothian and West Lothian are classified as being medium potential (shown in light green on Figure 7.4) meaning they have over 50 km^2 of the area underlain with mine workings.

Six authorities were classed as having small potential (shown in yellow) and four authorities were as classified as peripheral (shown in grey), though this does not discount sub-areas of being of interest. For example, Dumfries & Galloway, classed as peripheral, has an area of underground workings (approx. 20 km^2) in the north of the authority area, west of Sanquhar (Figure 7.5), that are close to the workings around New Cumnock in East Ayrshire (approx. 16 km to the west). Whilst most of the Dumfries & Galloway authority area has no coal mining (coal workings cover only 0.3% of total area), this concentrated area of coal mining in the north is not insignificant (46.8 million m^3) and could be worth investigating in collaboration with East Ayrshire, which is classified as a large coalfield area. Cross boundary potential is also the

[35] Despite having a small amount underground workings, three authorities (West Dunbartonshire, Scottish Borders and Perth & Kinross, Figure 7.3) were discounted from the classification altogether as they did not score highly enough.

[36] North Lanarkshire coal workings area = 253,154,927 m^2, whole North Lanarkshire area = 472,299,790 m^2

case for Edinburgh, Midlothian and East Lothian, where there is a concentrated area of mine workings to the east of Edinburgh (Figure 7.5). The collective volume of those three authorities is 373,923,256 m^3. Collaboration between local authorities will be discussed further in the following section.

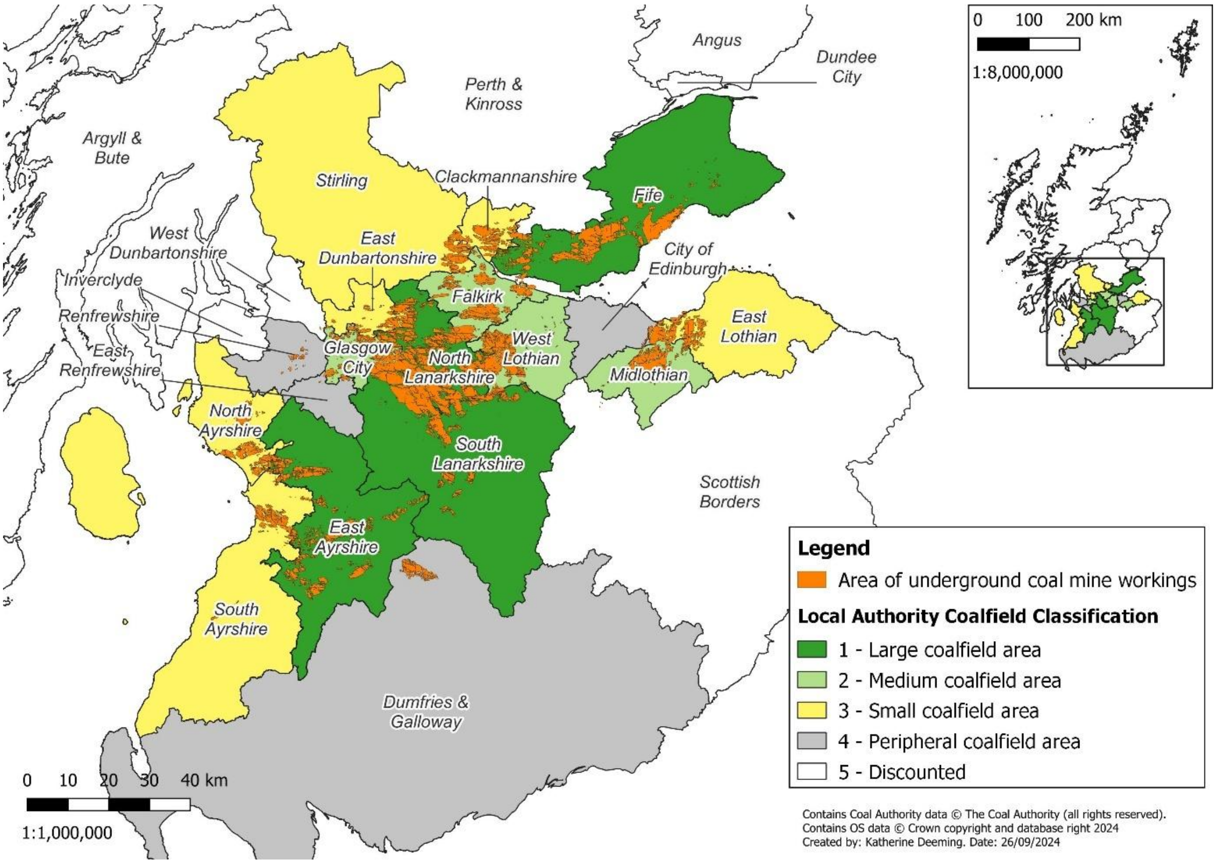

Figure 7.4: Local authority Coalfield Classification system in the Central Belt of Scotland with the area of underground coal mine workings shown in orange. Please note that the Isle of Arran is part of the North Ayrshire local authority area but there are no Mining Remediation Authority data for underground workings on the island. Contains data from MRA (2023c) and Ordnance Survey (2024b).

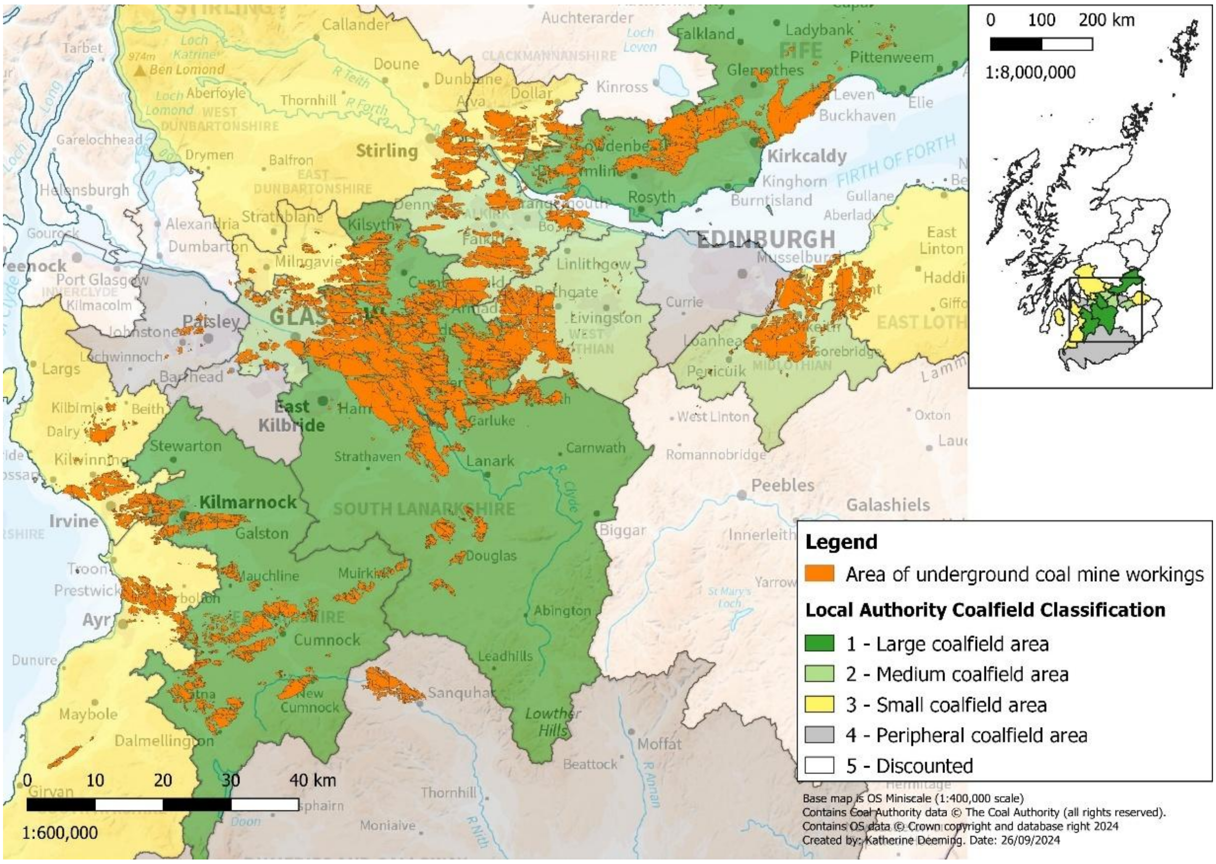

Figure 7.5: Coalfield classification with relief background map and the area of underground coal mine working shown in orange. Contains data from MRA (2023c) and Ordnance Survey (2014, 2024b).

7.5 Regional potential for minewater thermal storage

Figure 7.6 plots 25% of underground volume (Section 7.1) against total replacement demand (Chapter 6) for the 18 local authority areas that have a coalfield area (Section 7.4, Figure 7.5). Three authorities, North Lanarkshire, South Lanarkshire, and Fife, have a large volume of minewater thermal resources (Figure 7.6), and therefore high potential for storage, that is co-located with a good level of boiler replacement demand (between 30,000 and 40,000 homes built since 1997).

Glasgow City and City of Edinburgh both have very high replacement demand (>50,000) but low potential for storage, as they do not have large volumes of mine workings (Figure 7.6). Glasgow City was classified as having a medium coalfield area (Figure 7.4), but with a total of around 166 million m^3 (25% = 41 million m^3, Figure 7.6), there could be some local storage potential. Edinburgh City was only classed as peripheral coalfield area, so there would be limited potential for storage within the city limits. However, there is definite potential for cross-authority collaboration.

As discussed above, when Edinburgh City is considered with its neighbouring authorities of Midlothian and East Lothian, peripheral, medium and small coalfield areas respectively, then the region has a much larger volume than any of the three authorities individually (~373 million m^3). This also increases the lower replacement demand for majority rural Midlothian and East Lothian (replacement demands of 13,161 and 14,044 respectively, Table 7.6), and by combining with the higher urban demand provided by Edinburgh City (53,359, Table 7.6) to give a regional demand of over 80,000 (Table 7.6).

7.5.1 Regional clusters

As such, five regional clusters of three or more authorities (except Fife) have been produced based on the coalfield classifications from Section 7.4, by grouping large or medium coalfields with neighbouring small or peripheral coalfields and broad locations of the underground workings. The clusters are 'Greater Glasgow and Lanarkshire', 'Edinburgh and Lothian', 'Ayrshire and Sanquhar', 'Forth Valley' and 'Fife'. The regional clusters are shown on the local authority classification map from Section 7.4 in Figure 7.8 and are summarised in Table 7.6.

Fife is the only regional cluster made up of a single authority. It has a large underground volume of 657 million m^3 (Figure 7.3) and was classified as a large coalfield (Figure 7.4). Fife has the third largest total replacement demand of any local authority ~37,000, after Glasgow and Edinburgh (Figure 6.3). It is also geographically separate from the other large coalfield areas of North and South Lanarkshire, so it made sense for it to be its own cluster (Figure 7.8). Figure 7.8 shows that West Fife does have some workings which fall into the 'Forth Valley' cluster but for simplicity, they have not been included in that cluster, and Fife remains separate. However, collaboration between West Fife and the authorities of the 'Forth Valley' cluster could be beneficial.

Please note, West Lothian is included in the 'Greater Glasgow and Lanarkshire' regional cluster, as most of the coal mine workings are to the west of the local authority area close to the workings of North and South Lanarkshire (Figure 7.8). The peripheral coalfields of Renfrewshire and East Renfrewshire, to the west of Glasgow, have been omitted from the 'Greater Glasgow' and Lanarkshire regional cluster, as the majority of the coal mine workings are to the east of Glasgow City centre and only a small portion fall to the west of the city centre (Figure 7.8). Figure 7.7 plots 25% of the total mined volume against the replacement demand, with local authorities grouped into regional clusters.

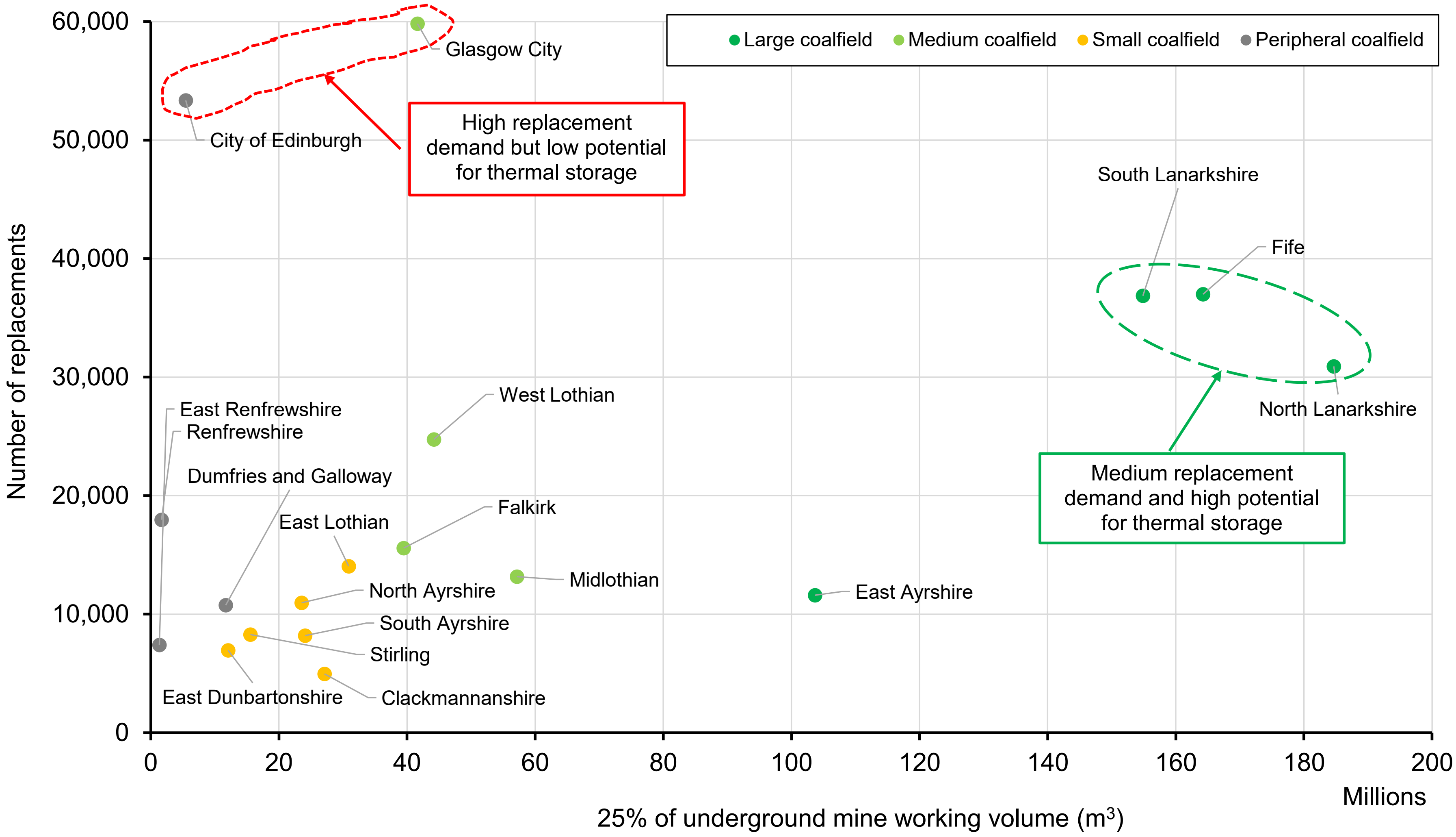

Figure 7.6: 25% of underground volume vs replacement demand by local authority. Contains data from Chapter 5 and 6.

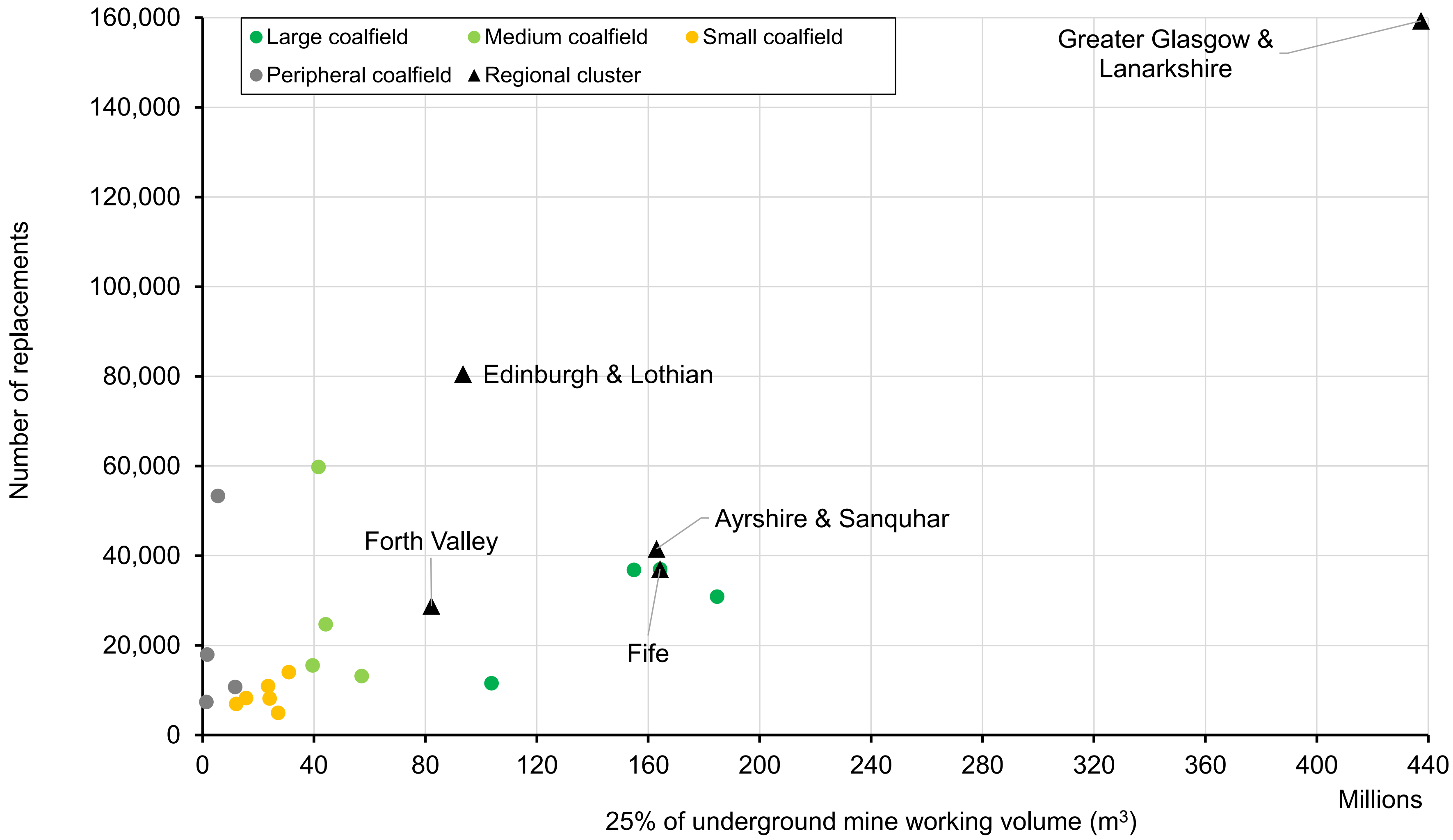

Figure 7.7: 25% of underground volume vs replacement demand by Regional Cluster (labelled). The individual local authorities are shown in the same colours as Figure 7.6

Table 7.6: Summary of regional clusters shown in Figure 7.7.					
Location (number of LAs)	**Coalfield class (*LA only*)**	**25% of underground volume (m^3)**	**Replacements**	**Area of coal mine workings (km^2)**	**Percent of total LA area**
Greater Glasgow & Lanarkshire (5)		**437,386,620**	**159,322**	**549**	**18%**
Glasgow City	*Medium*	*41,622,524*	*59,822*	*56*	*31.8*
North Lanarkshire	*Large*	*184,646,290*	*30,916*	*253*	*56.6*
South Lanarkshire	*Large*	*154,859,149*	*36,870*	*140*	*7.9*
West Lothian	*Medium*	*44,180,382*	*24,756*	*74*	*17.2*
East Dunbartonshire	*Small*	*12,078,275*	*6,958*	*26*	*14.9*
Edinburgh & Lothian (3)		**93,480,814**	**80,564**	**102**	**8%**
City of Edinburgh	*Peripheral*	*5,450,359*	*53,359*	*3*	*1.1*
Midlothian	*Medium*	*57,129,902*	*13,161*	*59*	*16.6*
East Lothian	*Small*	*30,900,553*	*14,044*	*40*	*5.7*
Fife (1)	**Large**	**164,230,004**	**36,995**	**146**	**11%**
Ayrshire & Sanquhar (4)		**162,960,777**	**41,524**	**226**	**2%***
North Ayrshire	*Small*	*23,528,675*	*10,961*	*41*	*4.5*
East Ayrshire	*Large*	*57,129,902*	*13,161*	*129*	*10.2*
South Ayrshire	*Small*	*24,067,149*	*8,195*	*36*	*2.9*
Dumfries & Galloway	*Peripheral*	*11,700,363*	*10,765*	*20*	*0.3*
Forth Valley (3)		**82,130,550**	**28,818**	**151**	**6%**
Stirling	*Small*	*15,548,407*	*8,283*	*31*	*1.4*
Clackmannanshire	*Small*	*27,130,719*	*4,957*	*40*	*24.4*
Falkirk	*Medium*	*39,451,424*	*15,578*	*80*	*25.4*

Abbreviations: LA = local authority. *Please note, if Dumfries and Galloway is excluded from the total local authority area, and only the three Ayrshire authorities are counted then the percentage underlain by coal mine workings is 6%.

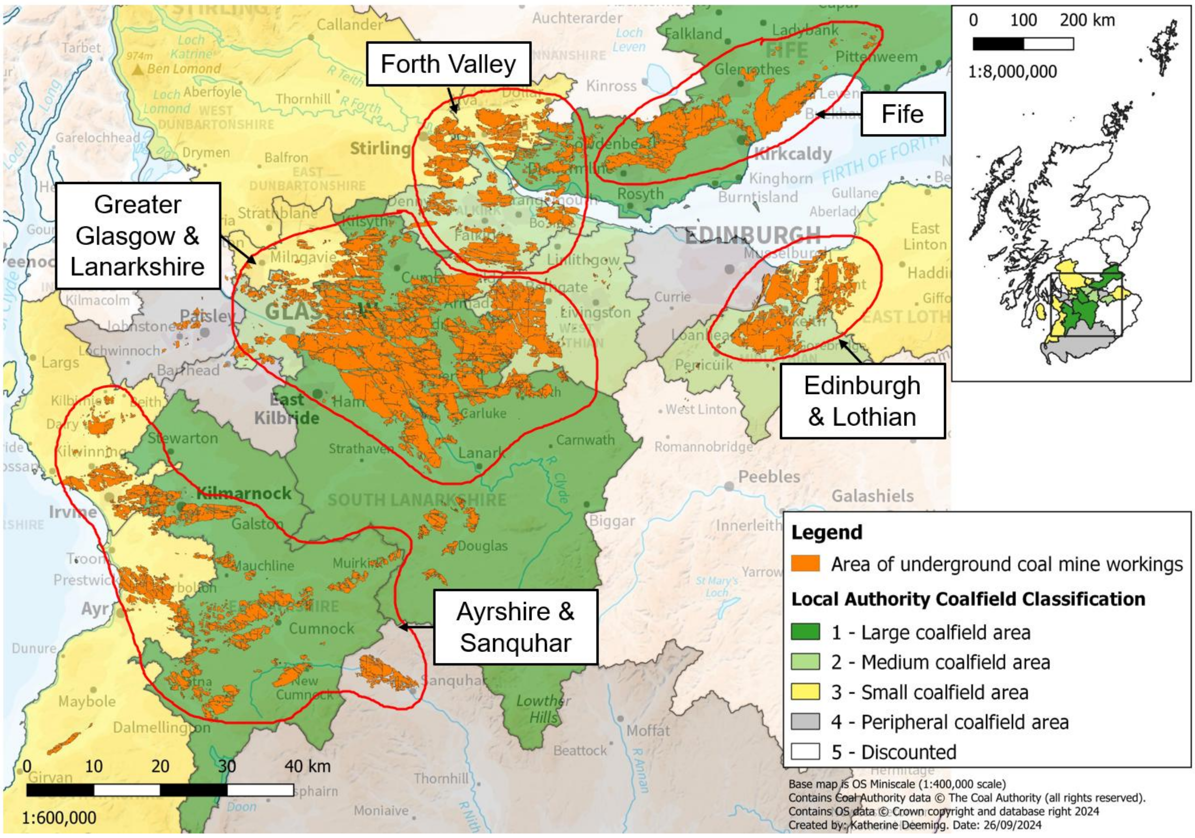

Figure 7.8: Map from Figure 7.5 with regional clusters from Figure 7.7 and Table 7.6 circled in red and labelled.

8. CHAPTER 8: Conclusions & recommendations

Minewater thermal resources are distinct from low carbon heating or thermal storage technologies. On one hand, they are similar to existing thermal storage technologies such as tank or pit thermal storage as they both use water to store heat underground. However, as shown in they can have volumes much greater than artificially constructed thermal stores (Section 7.2). On the other hand, like other sources of ambient heat they use heat exchangers and heat pumps to increase ambient heat to usable temperatures, but unlike other ambient heat sources they have a dual purpose of thermal storage and are more difficult to characterise and access.

Using minewater thermal resources presents a number of challenges. We have seen that there are several uncertainties with the data (Chapters 4 and 5), accessing the mines, and the potential heat capacity (Section 7.1), and the large upfront cost of characterising the mine, carrying out ground investigation (Chapter 3). Whilst these challenges mean that minewater thermal resources need special consideration (i.e. from geoscientists etc. Chapter 3), they should not be excluded from conversations about low carbon heating solutions. Minewater thermal resources should be considered among the many local heat sources at each location. Minewater might be able to provide higher temperatures and the year-round constant heat levels compared to another heat source, such as a river, but the higher cost of characterising the mine, time spent accessing data and permits, or extensive site investigation must be balanced against the value of the extra few degrees of heat.

Participants in Chapter 3 felt that thermal storage was the key advantage of using minewater resources, and that there are relatively few other ways of storing large amounts of heat for a long enough period to allow for inter-seasonal balancing of the system. As has been demonstrated at Heerlen, eventually the minewater heat reservoir began to cool down (Section 2.2.1.1, Verhoeven *et al.*, 2014) and thermal storage need to be incorporated into the system to balance out the heat losses. If mine shafts or underground workings are proven to hold onto the heat for sufficiently long, then using abandoned mines for inter-seasonal thermal storage should be pursued preferentially to using them just for heating.

Scotland only has 20 years to decarbonise 2.25 million homes currently on the mains gas network. As such, it is important that time and resources are not wasted investigating a solution that may not serve a large amount of heat demand in the short term. My estimates have shown that minewater thermal resources could only provide heating for <5% of the homes in Scotland (Section 7.1). To justify the costs of feasibility and construction, there would need to be a concentred cluster of houses that would be using the heat, and there would need to be back-up options in case the mine system stopped providing heat (true for any ambient heat source).

Minewater thermal technologies are a new development in Scotland and the UK, and as such the regulations are not ready to support deployment at scale (Section 3.3.3).

Instead of considering minewater for domestic heating, minewater thermal heating and cooling schemes or thermal storage schemes could be developed alongside the development of data centres, which will become more widespread, to provide cooling, or for industrial greenhouses to ensure food security as the climate changes. Then minewater resources could be incorporated into these new developments from the beginning rather than having to retrofit existing heating systems. This could work for large mines in rural areas that are away from large settlements heat demand, such as Barony. One of the main problems with minewater resources especially in rural areas is that the settlements are quite small and the amount of capital that would be needed to invest in setting up a minewater scheme is not viable for those communities. In urban areas where there is more heat demand, there are fewer mines, e.g. central Glasgow and Edinburgh (Figure 7.6). Despite these shortcomings, minewater thermal resources are worth investigating in terms of thermal storage, as they provide a large-scale thermal store that could be used in conjunction with other heat sources. The importance of this potential should not be overlooked.

8.1 Conclusions

- Storage is a key advantage that distinguishes minewater thermal resources from other low carbon heating solutions (Chapter 3). There is a large potential for storage across Scotland, with the best estimate being around 10^9 m^3 of void space in abandoned coal mines (Chapter 5). However, there are still many uncertainties with that estimate due to the issues of data quality discussed in Chapters 5 and 7.
    - If used for heat extraction, 25% of the estimated total volume could heat between 5000 and 84,000 homes.
- Scotland also has an abundance of abandoned mine shafts, which if accessible, could provide a storage volume of 2.9 $x10^6$ m^3.
- Chapter 3 showed that stakeholders felt that cost both upfront and operational, was a key barrier of using minewater thermal resources.
- Five regional clusters were identified where local authorities could work together to maximise their storage potential and replacement demand (Chapter 7)
    - The Greater Glasgow and Lanarkshire regional cluster had the highest potential for using minewater thermal resources, due to its large volume of void space, and high demand for heating replacement. This would need to see five local authorities work together.

- Replacement of heating systems will be spatially variable across the country, but in the next 25 years, over 500,000 homes built since 1997 will need a replacement heating system. (Chapter 6)
    - The estimate of 84,000 homes heated by minewater from Chapter 7 could provide heat for ~16% of Scottish homes (built since 1997) needing a heating replacement from Chapter 6.
- Due to their scale and cost, minewater projects will not be implemented by individuals for their homes, they have to be linked to district heat networks for housing estates, villages, or towns in order to make the investment and large capital cost worthwhile. Therefore, will need the involvement of planning authorities and government to coordinate how these resources will contribute to heat decarbonisation. There is a need for more strategic planning around where minewater resources could best be utilised in Scotland.

8.2 Recommendations for future research and practice

8.2.1 Research

- Investigation of public perception of minewater thermal in Scotland. There has been very little research on what these communities actually think about the mines in their vicinity being used for this purpose, and testing of a relatively novel (in the UK) technology on communities who have already been through so much when it comes to the history of mining is not ideal (Roberts *et al.*, 2023).
- The approach in Chapter 6 could be extended by predicting when the heat pumps which replaced the boilers, will need replacing or by finding the newbuild estates in within authorities and when they were constructed to allow for more spatially detailed prediction of future heating replacement demand.
- Scotland was the case study for this spatial analysis, but this spatial and temporal approach could be used to assess minewater thermal resources in other mining regions across the UK or elsewhere.
- Could minewater thermal resources be better used to serve industrial heating or cooling demand? E.g. heat for industrial greenhouses, other industrial processes, or cooling for data centres.

8.2.2 Practice

- There is a need for more cross-boundary local authority collaboration because mines cross local authority boundaries and do not always correspond with LHEES.

- The regional approach coal also be investigated by the Mining Remediation Authority for the opportunity mapping, as the current maps for English cities are bound by local authority boundaries rather than but underground mine workings.
- Similarly, the regional clusters could be investigated in the context of regional funding or programmes such as the Ayrshire Energy Masterplan (South Ayrshire Council, 2025) or Stirling and Clackmannanshire Regional Energy Masterplan (Clackmannanshire Council, 2023).

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9.1 Coal mine abandonment plan references

Seven coal mine abandonment plans for Seaforth Colliery in East Ayrshire were obtained in November 2023 from the Mining Remediation Authority (The Coal Authority at the time of issue). Issued by: The Coal Authority, Property Search Services, 200 Lichfield Lane, Berry Hill, Mansfield, Nottinghamshire, NG18 4RG on 6th November 2023 to Katherine Deeming, University of Strathclyde.

Information common to all seven abandonment plans	
Catalogue number	S146
Sheet number	99 9999
County	Ayrshire
Date abandoned	01/01/1955
Date received	15/09/1955
Working type	Underground
Original scale	2 CHAINS TO 1 INCH (1 TO 1584)

Information for individual plans			
Sheet name	**Seam name**	**Colliery name**	**Figures**
1 OF 7	FIVE FEET	SEAFORTH 1 & 2	Figure 5.8
2 OF 7	EIGHT FEET	SEAFORTH NO 1	Figure 5.11A
3 OF 7	EIGHT FEET	SEAFORTH NO 1	
4 OF 7	THREE FEET	SEAFORTH NO 1	
5 OF 7	FOUR FEET & DIAMOND	SEAFORTH NO 1	Figure 5.7, Figure 5.11B
6 OF 7	MUSSELBAND	SEAFORTH NO 1	
7 OF 7	BLACKBAND	SEAFORTH NO 1	

10. Appendices

10.1 Appendix 1 – Storage volume of UTES schemes sorted by country

Table 10.1: Storage volume of UTES schemes sorted by country.

Country	Number of schemes	Total volume (m^3)
Germany	19	109,680
Denmark	10	532,500
Sweden	4	124,700
Austria	4	150,000
Finland	2	191,500
The Netherlands	2	24,715
China	1	15,000
Italy	1	500
South Korea	1	84,000
Switzerland	1	1000
Total	**45**	**1,233,595**

10.2 Appendix 2 - Thermal storage schemes sorted by storage type

Table 10.2: Thermal storage schemes sorted by storage type and the total and mean volume and demand for each type

Store type	Number of schemes	Total volume (m^3)	Mean volume (m^3)	Total demand (MWh)	Average demand (MWh)
PTES	13	566,050	43,542	200,276	15,406
TTES	7	33,450	4,779	13,695	1,956
ATES	2	43,000	21,500	5592	2796
CTES	1	120,000	120,000	5500	5500
Total	**23**	**762,500**	**33,152**	**225,063**	**9,785**

10.3 Appendix 3 – Data fields in the MRA mine entries dataset

Table 10.3: Data fields in the Mining Remediation Authority mine entries dataset

Data field	Description from MRA guidance (MRA, 2024c)	Type of data	Data field coverage
OBJECTID	GeoDB ID number	Identification	100%
GLOBALID	A Universal Unique Identifier automatically assigned by the geodatabase.	Identification	100%
RFRNC	Reference: The reference number of the mine entry derived from the km square location.	Identification	100%
NAME	Local name of mine entry	Identification	100%
COLLIERY_NAME	Name of colliery this mine entry is associated with. This attribute is rarely populated.	Identification	1%
TYPE	Mine entry type. Denotes if mine entry is a shaft or an adit.	Mine Entry Characteristic	100%
MI_CODE	Mineral worked. Most are coal but the Mining Remediation Authority also holds records for other minerals on the system in cases where	Mine Entry Characteristic	100%

	they were worked with the coal or close to the coal seams.		
DEPTH	Depth of mine entry in metres from surface. The Mining Remediation Authority will only provide the depth of a mine entry where this is known.	Mine Entry Characteristic	32%
SHFT_DM	Actual diameter of mine entry in metres.	Mine Entry Characteristic	3%
ASUM_DM	Assumed shaft diameter: Where information about the diameter of a shaft is not known it will be assumed. The assumption will be based upon comparison with other shafts in the vicinity, the likely date it was sunk and any other relevant information.	Mine Entry Characteristic	98%
TRTMT_IN	Treated Indicator: True or False. True denotes that the Mining Remediation Authority holds record of treatment details on our database. False denotes no record of treatment details are available on the database. Treatment details are generally only known post coal industry nationalisation in 1947. If this field is TRUE, the data must be requested from the Mining Remediation Authority for a specific shaft.	Mine Entry Characteristic	100% True = 15% False = 85%
TRTMT_DT	Date the mine entry was treated, if known.	Mine Entry Characteristic	5%
DRIFT_DP	Depth in metres of surface deposits at mine entry xy, where known.	Mine Entry Characteristic	4%
SOLD_IN	Conveyed Indicator: True or False. True equals the mine entry has been conveyed.		98.9% True = 0.3% False = 98.6%
SOLD_DT	The date the mine entry was conveyed.		0.2%
OPENCAST_F	Opencast Flag: True or False. True denotes we believe this mine entry to have been removed by subsequent surface mining activities.		99% True = 0.1% False = 98.9%
DPARTURE	An assumed distance representing the potential difference between a mine entry's plotted position and its true position. This assumed distance will be between 0 to 10 metres and will depend, inter alia on age, scale, condition and status of the source plan from which the position is taken.		100%
VERIFIED	Verified indicator: True or False. An attribute that determines whether manual intervention is required. Where verified indicator equals False then further information should be sought from the Mining Remediation Authority when used in the context of a mining search report, for example CON29M		100% True = 100% False = 0%

10.4 Appendix 4 – Data fields in the MRA underground workings dataset

Table 10.4: Data fields in the Mining Remediation Authority underground workings dataset (MRA, 2023c) from the user guide for the dataset (MRA, 2015). An asterisk indicates data fields which were included in the shapefile dataset but not included in the 2015 guidance*

Data field code	Data field name	Definition of data field (MRA, 2015)	Data coverage
OBJECTID	OBJECTID	File GeoDB ID number	100%
GLOBALID	GLOBALID	Globally Unique Identifier (GUID)	100%
L_RFRNC	License reference	Unique Coal Authority Licence Reference	0%
MI-CODE	Mineral code	Mineral worked.	100%
PHASED	Phased	Phased indicator = TRUE/FALSE. Phased workings: A planned working that has been split into a number of parts.	100% TRUE = 0.04% FALSE = 99.96%
DIP_RATE	Dip	The magnitude in degrees of the true or steepest inclination of the strata relative to the horizontal.	99%
DIP_DRN	Dip direction	The direction of the true or steepest inclination of the strata relative to the horizontal.	99%
NAME	Panel name	An individual area of working within a seam.	100%
*PANEL	Panel code		100%
SE-THKNS	Extraction thickness	Thickness of coal extraction in centimetres	100%
SE_CODE	Seam code	A unique alphanumeric identifier used to define a specific seam.	100%
COLLIERY_NAME	Colliery name	Name of colliery this underground working is associated with.	100%
*TYPE	Type of mining	The shapefile data distinguishes whether a panel has been worked using "Pillar and Stall" or "Normal (Total Extraction)"	100%

10.5 Appendix 5 – Data fields in Oglethorpe (2006)

Table 10.5: Data fields in Oglethorpe (2006) and whether they were included in the data collection for Chapter 5.

Data field	Definition of data field	Included in data collection?	Percentage of collieries with data
Colliery name	Local name of the colliery	Y	100%
Grid Reference	Eight figure grid reference	Y	100%
Location	Nearest town or village	Y	97%
Parish	Parish that the colliery sits within	N	n/a
Region/ District	Historic region that the colliery sits within	N	n/a
Council	Current local authority area	Y	100%
Previous Owners	Companies or individuals who owned the colliery prior to nationalisation	N	n/a
Types of coal	Lists types of coal mined at the colliery, including, anthracite, coking, gas, house, manufacturing, and steam, as well as byproducts such as fireclay.	Y	84%
Year of sinking/	Known dates when the colliery or individual shafts were sunk	Collected as one data field	98%
Year production commenced.	Known dates when coal production started at the colliery		
Year closed.	Date production ceased	Y	99%

Year abandoned	Date the workings were officially abandoned, often a significant time after closure	Y	69%
Average workforce	Mean number of surface and underground workers during a colliery's lifetime after 1947	Y	92%
Peak workforce	The largest number of surface and underground workers after 1947 when the workforce was the greatest	Y	91%
Peak year	The year after 1947 when the workforce was the greatest	Y	90%
Number of shafts/ mine details	Details of the mine shafts at the colliery including eight figure grid references and whether the mining took place underground or on the surface as opencast.	Y	96%
Depth of shafts	Depth of the mine shafts in metres	Y	
Output per day (tons) (data in 1948)	Information relating to the questionnaire filled in by the colliery manager in the later 1940s after nationalisation – does not exist for collieries sunk after 1947	Y	78%
Output per annum (tons) (data in 1948)		Y	
Type of mining	List what type of mining was used at the colliery such as, longwall or stoop and room.	Y	

10.6 Appendix 6 – Summary of data on panels from the MRA (2023c) underground workings dataset for the four collieries in this study

Table 10.6: Summary of data on panels from the MRA (2023c) underground workings dataset for the four collieries in this study. Sorted by whether they give an under or and overestimate of volume/

	Colliery	Number of panels	Sum of all thicknesses (cm)	Av. Thickness per panel (cm)
M1 underestimate	Seaforth	6	365	61
	Barony	30	5143	171
M 1 overestimate	Cardowan	162	15,653	97
	Killoch	106	20,671	195

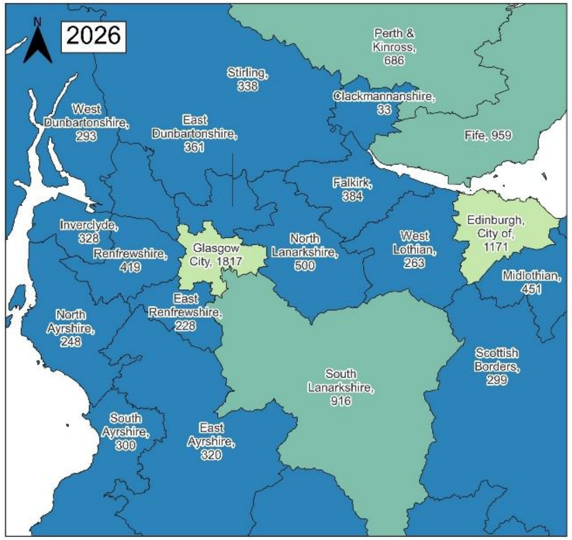
10.7 Appendix 7 – Number of heating replacements per local authority

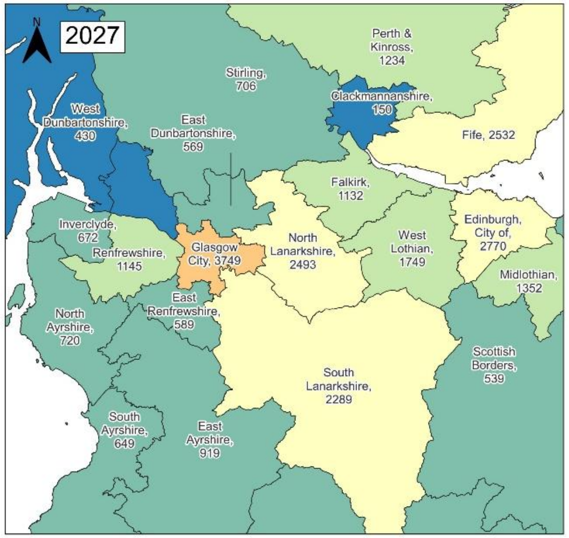
Table 10.7: Number of heating replacements per local authority. Contains data from Scottish Government (2024e) and Scotland's Census (2022).

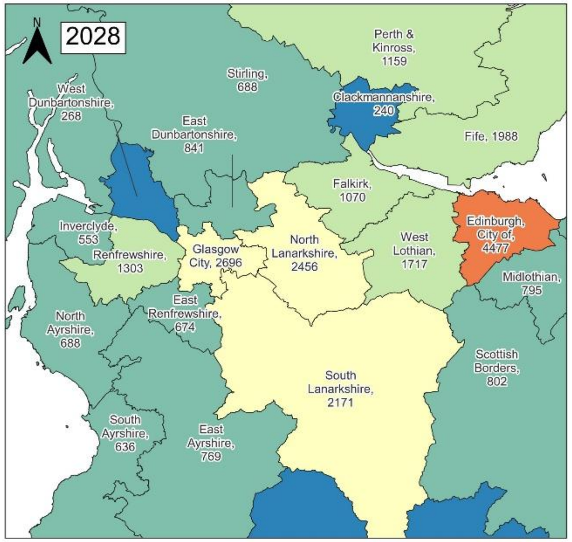
	Local authority	Total number of replacements	Replacements as a % of total dwellings in each LA
1	Glasgow City	59,822	20.4%
2	City of Edinburgh	53,359	22.3%
3	Fife	36,995	21.8%
4	South Lanarkshire	36,870	24.9%
5	Aberdeenshire	34,012	29.4%
6	Highland	31,198	27.9%
7	North Lanarkshire	30,916	20.4%
8	West Lothian	24,756	31.0%
9	Aberdeen City	21,487	19.6%
10	Perth and Kinross	19,383	27.7%
11	Renfrewshire	17,965	20.7%
12	Falkirk	15,578	21.5%
13	East Lothian	14,044	28.8%
14	Midlothian	13,161	32.1%
15	Dundee City	12,022	17.2%
16	Scottish Borders	11,722	21.1%
17	East Ayrshire	11,603	20.9%
18	North Ayrshire	10,961	17.1%
19	Dumfries and Galloway	10,765	15.2%
20	Moray	10,626	24.6%
21	Angus	8994	16.6%
22	Stirling	8283	20.5%
23	South Ayrshire	8195	15.6%
24	East Renfrewshire	7405	18.6%
25	West Dunbartonshire	7294	17.1%
26	Inverclyde	7223	19.3%
27	East Dunbartonshire	6958	15.0%
28	Argyll and Bute	6761	16.1%
29	Clackmannanshire	4957	20.6%
30	Na h-Eileanan Siar	3304	26.0%
31	Orkney Islands	2976	28.0%
32	Shetland Islands	2826	26.7%
TOTAL		**552,421**	**22%**
Mean per local authority		***17,263***	

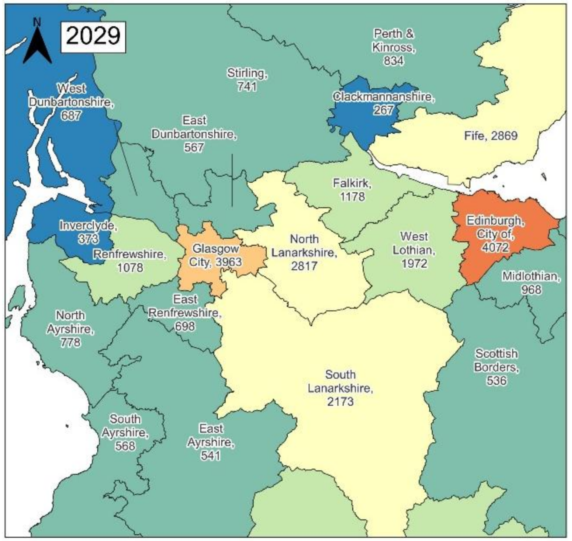
10.8 Appendix 8 – maps of Central Belt heating replacements from 2026 to 2039.

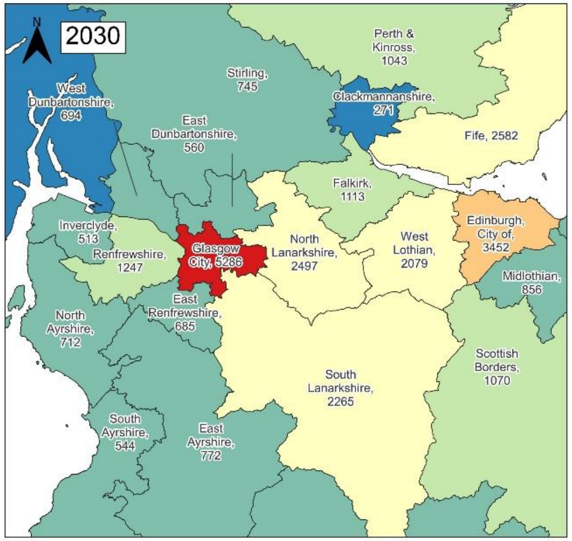
Contains data from Scottish Government (2024e). Local authority boundaries from Ordnance Survey (2024)

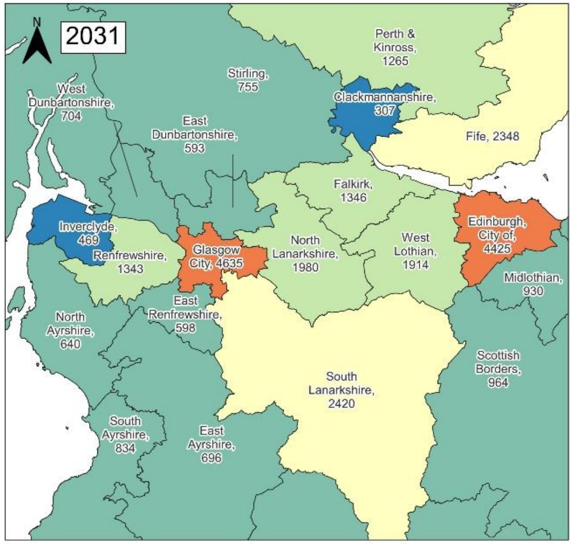


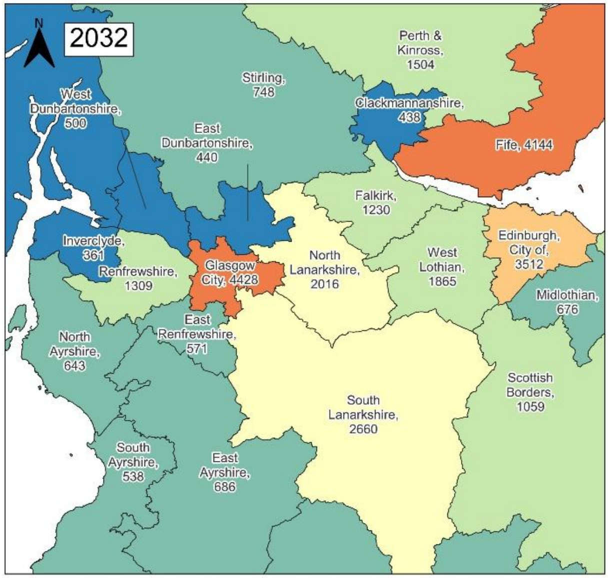


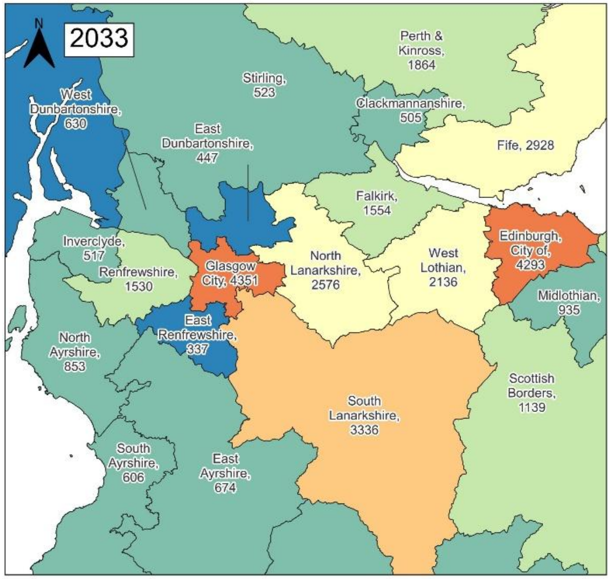


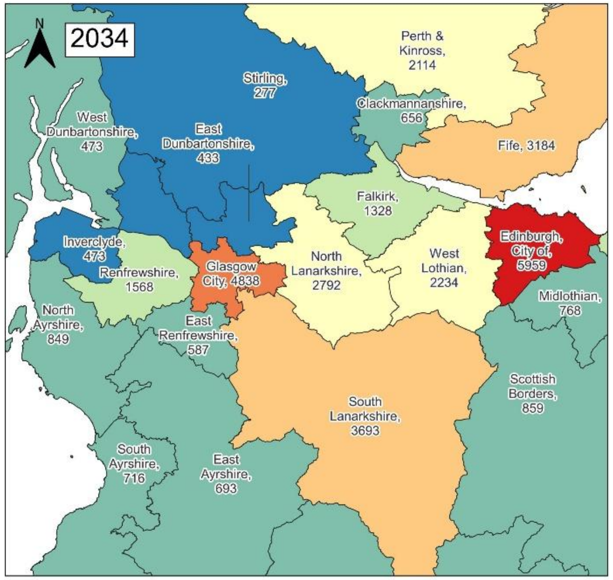


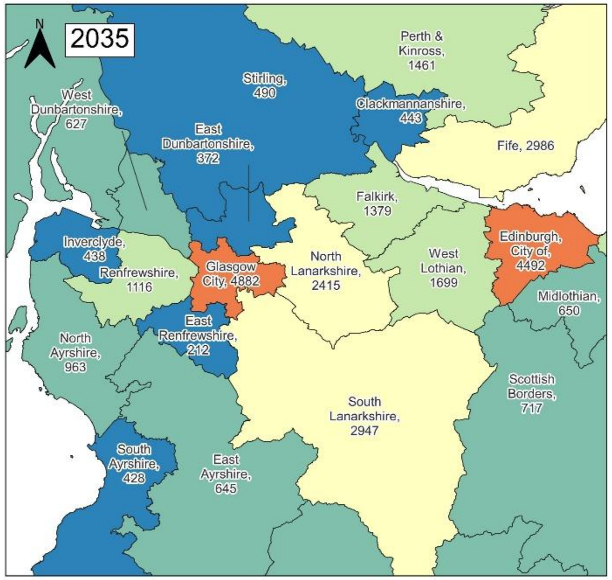


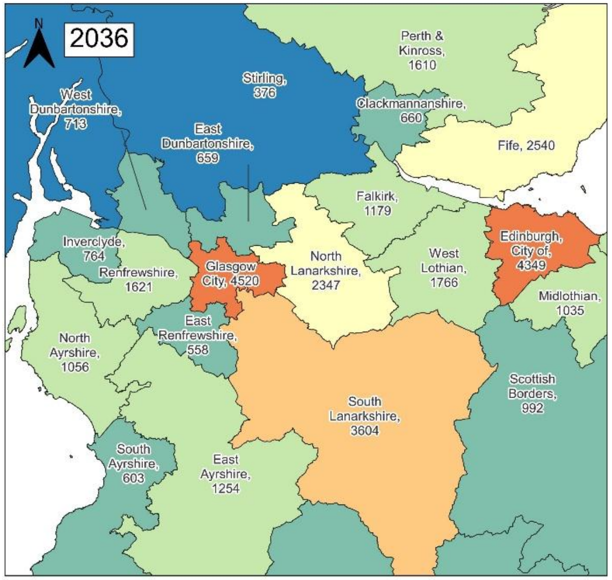


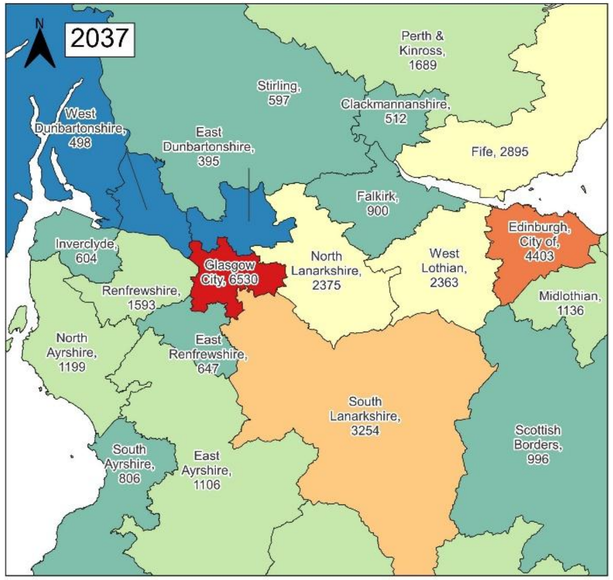

2032
N
Perth & Kinross, 1504
Stirling, 748
West Dunbartonshire, 500
Clackmannanshire, 438
East Dunbartonshire, 440
Fife, 4144
Falkirk, 1230
Inverclyde, 361
Edinburgh, City of, 3512
North Lanarkshire, 2016
West Lothian, 1865
Renfrewshire, 1309
Glasgow City, 4428
Midlothian, 676
East Renfrewshire, 571
North Ayrshire, 643
Scottish Borders, 1059
South Lanarkshire, 2660
South Ayrshire, 538
East Ayrshire, 686

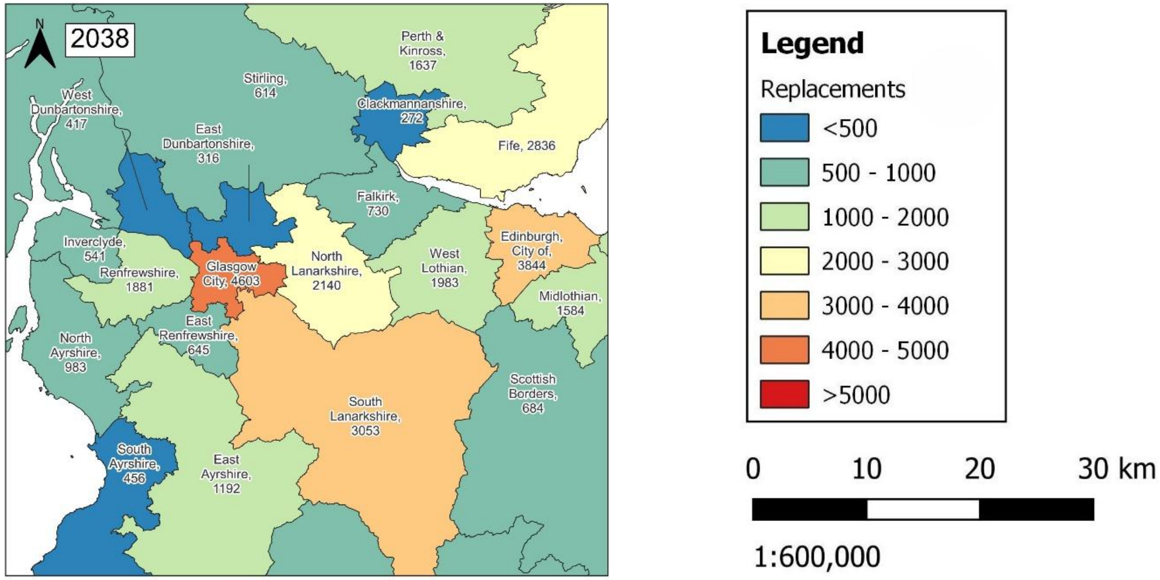

2033
N
Perth & Kinross, 1864
Stirling, 523
West Dunbartonshire, 630
Clackmannanshire, 505
East Dunbartonshire, 447
Fife, 2928
Falkirk, 1554
Inverclyde, 517
Edinburgh, City of, 4293
North Lanarkshire, 2576
West Lothian, 2136
Renfrewshire, 1530
Glasgow City, 4351
Midlothian, 935
East Renfrewshire, 337
North Ayrshire, 853
Scottish Borders, 1139
South Lanarkshire, 3336
South Ayrshire, 606
East Ayrshire, 674


2034
N
Perth & Kinross, 2114
Stirling, 277
West Dunbartonshire, 473
Clackmannanshire, 656
East Dunbartonshire, 433
Fife, 3184
Falkirk, 1328
Inverclyde, 473
Edinburgh, City of, 5959
North Lanarkshire, 2792
West Lothian, 2234
Renfrewshire, 1568
Glasgow City, 4838
Midlothian, 768
North Ayrshire, 849
East Renfrewshire, 587
Scottish Borders, 859
South Lanarkshire, 3693
South Ayrshire, 716
East Ayrshire, 693


2035
N
Perth & Kinross, 1461
Stirling, 490
West Dunbartonshire, 627
Clackmannanshire, 443
East Dunbartonshire, 372
Fife, 2986
Falkirk, 1379
Inverclyde, 438
Edinburgh, City of, 4492
North Lanarkshire, 2415
West Lothian, 1699
Renfrewshire, 1116
Glasgow City, 4882
Midlothian, 650
East Renfrewshire, 212
North Ayrshire, 963
Scottish Borders, 717
South Lanarkshire, 2947
South Ayrshire, 428
East Ayrshire, 645


2036
N
Perth & Kinross, 1610
Stirling, 376
West Dunbartonshire, 713
Clackmannanshire, 660
East Dunbartonshire, 659
Fife, 2540
Falkirk, 1179
Inverclyde, 764
Edinburgh, City of, 4349
North Lanarkshire, 2347
West Lothian, 1766
Renfrewshire, 1621
Glasgow City, 4520
Midlothian, 1035
East Renfrewshire, 558
North Ayrshire, 1056
Scottish Borders, 992
South Lanarkshire, 3604
South Ayrshire, 603
East Ayrshire, 1254


2037
N
Perth & Kinross, 1689
Stirling, 597
Clackmannanshire, 512
West Dunbartonshire, 498
East Dunbartonshire, 395
Fife, 2895
Falkirk, 900
Inverclyde, 604
Edinburgh, City of, 4403
North Lanarkshire, 2375
West Lothian, 2363
Glasgow City, 6530
Renfrewshire, 1593
Midlothian, 1136
East Renfrewshire, 647
North Ayrshire, 1199
South Lanarkshire, 3254
Scottish Borders, 996
South Ayrshire, 806
East Ayrshire, 1106


2038
Perth & Kinross, 1637
Stirling, 614
West Dunbartonshire, 417
Clackmannanshire, 272
Fife, 2836
East Dunbartonshire, 316
Falkirk, 730
Inverclyde, 541
Renfrewshire, 1881
Glasgow City, 4603
North Lanarkshire, 2140
West Lothian, 1983
Edinburgh, City of, 3844
Midlothian, 1584
East Renfrewshire, 645
North Ayrshire, 983
South Lanarkshire, 3053
Scottish Borders, 684
South Ayrshire, 456
East Ayrshire, 1192
Legend
Replacements
<500
500 - 1000
1000 - 2000
2000 - 3000
3000 - 4000
4000 - 5000
>5000
0 10 20 30 km
1:600,000

10.9 Appendix 9 – Regions used in Chapter 6 analysis

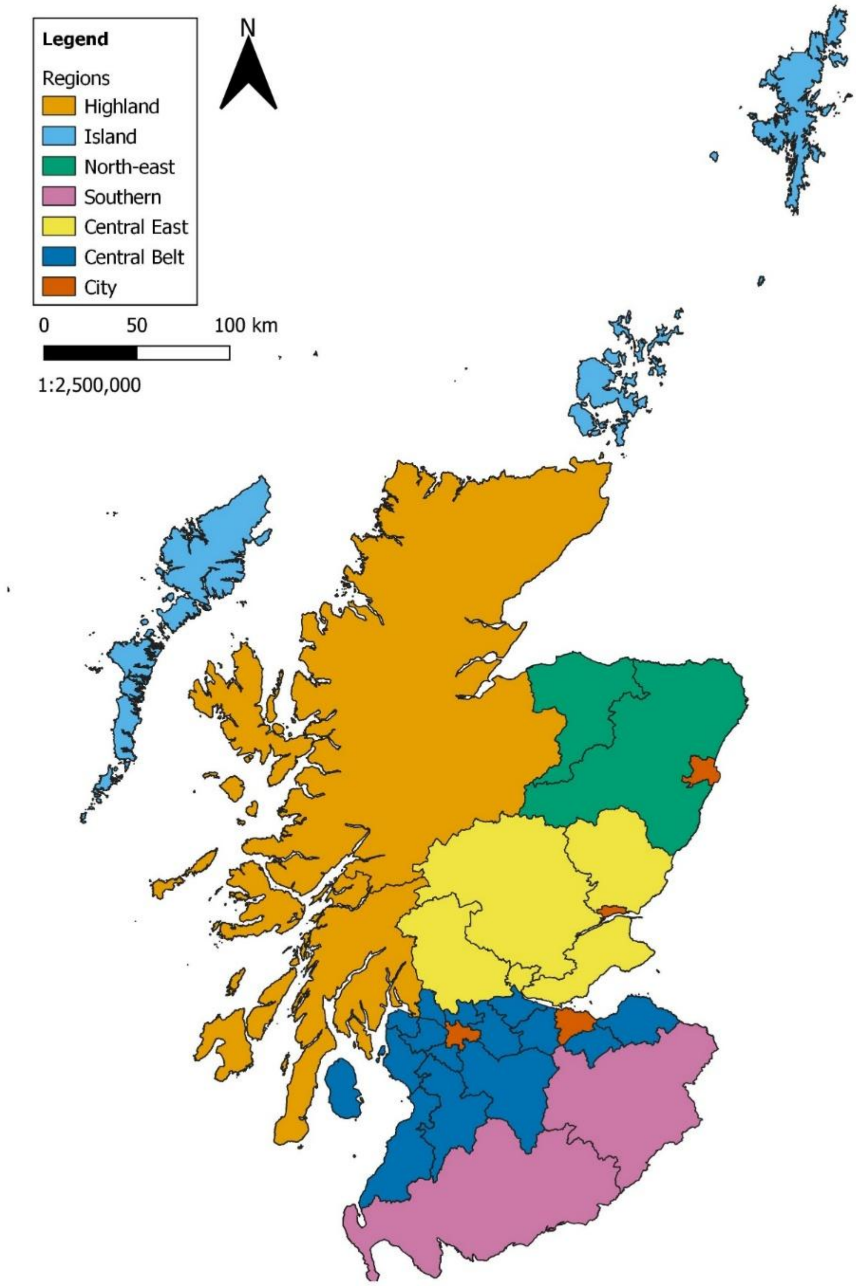


Figure 10.1: Regions used for regional analysis in Section 6.3.3.

10.10 Appendix 10 – Coalfield classification methodology

The overlap analysis function in QGIS was used to give the amount of overlap of coal underground workings (UG) and local authority (LA) area in metres squared. The initial overlap analysis showed that 21 of the 32 local authority areas in Scotland overlapped with the coal fields. However, some local authority areas had very small amounts of the underground workings within them. For example, a local authority area could contain a very small amount of underground workings and would still be included in a basic overlap analysis of the underground workings with local authority area, despite having no real prospects for minewater heating or storage.

I used three classifications to sort the data from the overlap analysis. Each local authority was assigned a number between 1 (highest) and 4 (lowest), using an IF function on Excel.

- Classification 1: The **area** in kilometres squared of underground workings in each local authority area. All the individual panels of the underground workings have been flattened into one layer to define a surface area where there are underground workings.
- Classification 2: The **volume** in metres cubed of underground mine volume in each local authority area
- Classification 3: The **percentage** of the local authority area which was underlain by underground coal workings

Table 10.8: Classification criteria used to classify local authority coalfield areas.

If the product of the three classifications is:	Classification	Count
Less than or equal to 3	Large	4
Less than 15 but greater than 3	Medium	4
Less than 30 but greater than 15	Small	6
Greater than 30	Peripheral	4
Greater than 60	Discounted	14

I multiplied the three classifications together to get a product, which was then classified with an IF function based on the criteria in Table 10.8. If an authority had scored 1 in all three of the classifications, then its product would be 1 and it could be classified as ‘Large’. But if an area had a classification product of more than 60, it would have had scored 4 all three classifications and it was discounted, because it would only have a very small area of underground workings in the local authority area both in-terms of the actual UG and relative to the total local authority area. Therefore, the local authorities would probably not be interested in developing the minewater resources in their area.

For example, in West Dunbartonshire only 0.28 km^2 of the local authority area is underlain by underground workings (0.2% of local authority area) and the total volume of those workings is 581,099 m^3. This means that West Dunbartonshire scored 4 in all three classifications meaning it was discounted, despite having some underground workings. Conversely, in Dumfries & Galloway only 0.3 % of the local authority area contained underground workings, but this was an area of 19.9 km^2 which could be worth investigating, but because D&G is so large it was only a small percentage of the total area, therefore it was classified as peripheral (Table 4).

Table 10.9: Examples of the five different local authority and underground workings overlap classifications

Local authority	**Classifications**			**Product**	**Final Classification**
	1 (area of LA)	**2 (mine volume)**	**3 (% of LA)**		
North Lanarkshire	1	1	1	1	Large
Glasgow City	2	3	1	6	Medium
North Ayrshire	2	3	3	27	Small
Dumfries and Galloway	3	4	4	48	Peripheral
West Dunbartonshire	4	4	4	64	Discounted