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Nurturing a New Industry Rooted in Geoscience: Stakeholder Insights on Minewater Thermal in Scotland

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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.

Keywords: geoscience, minewater, heat decarbonisation, sustainable geoscience, low carbon geoenergy, stakeholder interviews

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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, 2023b). 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; Abesser and Walker, 2022; Gardiner et al., 2023). Deep geothermal can provide electricity and high enthalpy heat (AECOM, 2013; 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; Brémaud et al., 2024 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.

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; Adams, 2023; The Coal Authority, 2023a; IEA, 2023a), 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., 2022; 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 m below ground level (m bgl) to 40°C at 1,200 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.

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, 2023a). 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, 2023b).

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, 2022; 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.

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 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

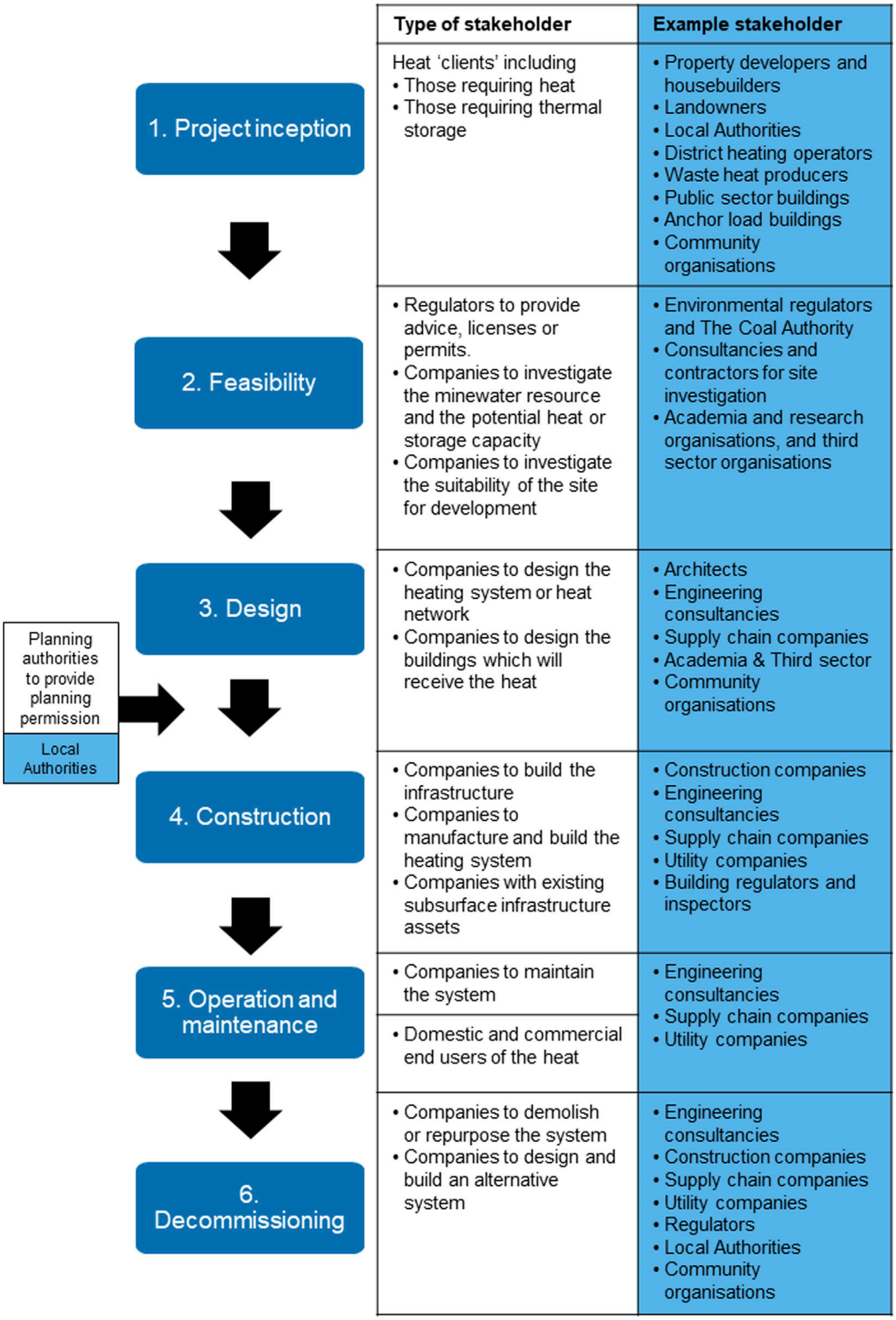

FIGURE 1 | Potential stakeholders who could be involved in delivery, regulation, or end-use of a minewater thermal project, defined by the stages of a project life cycle. Note: This list is not exhaustive and will vary with project type and context.

TABLE 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 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

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 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 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 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 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 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 60 codes that were grouped into four catagories (perceived advantages, perceived disadvantages, information required, and wider issue) to be analysed in more detail.

FIGURE 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.

RESULTS

The range of stakeholders involved across the lifecycle of a minewater thermal (MWT) resource project are shown in **Figure 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.

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

TABLE 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)	**4**	**4**	**3**	**3**	**2**	**2**

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 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 particiapnt 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.

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** 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).

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, and AT2; **Table 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).

Existing Skills and Labour Needed for Minewater Thermal Projects

Four interviewees from four stakeholder groups (L1, C3, SC1, and 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*

TABLE 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**

the UK" (SC1). However, all these existing skills need to be organised and coordinated to develop a future minewater thermal industry: "*All of the elements exist; they just need to be kind of collected in the right way"* (C3).

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.

Potential for Community Benefits

Three interviewees from two stakeholder groups (C2, AT1, and 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).

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.

Interviewee Perceptions: Disadvantages or Barriers of Minewater Thermal

Potential drawbacks and barriers to MWT identified by interviewees are summarised in **Table 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.

Cost of Minewater Thermal Projects

Cost, the most discussed challenge, was raised by four participants across three stakeholder groups (D1, D4, C3, U1; **Table 4**). 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).

Pre-Construction/Feasibility Risks and Technical Complexity

Feasibility risks and technical complexity were mentioned as a disadvantage by three participants (C1, C3, and 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).

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.

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.

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 5**.

TABLE 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	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**

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 a growing shortage of skills, labour, and, products were mentioned by five interviewees across four stakeholder groups (D2, L1, C2, C3, and AT2). Two interviewees (D2, AT2) felt that that there are currently not enough heat pump 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).

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 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[1] 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).

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, and 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 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).

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, and 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-

[1]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).

TABLE 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**

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.

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).

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 6**. Themes were common across interviewees, rather than specific to particular stakeholder groups or individuals.

Information to Build Trust or Confidence in the Technology

Three interviewees (D4, C1, and 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, and 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).

Mapping Heat Supply and Demand

Four interviewees from three stakeholder groups (C2, L1, AT1, and AT2; **Table 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).

Cost or Financial Risks

Three participants (D4, L1, and 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).

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.

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, 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 and 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 policymakers (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, 2022).

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**). 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 5**. For each topic area (resource, cost, and people) we explore the role of geoscientists in turn.

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.

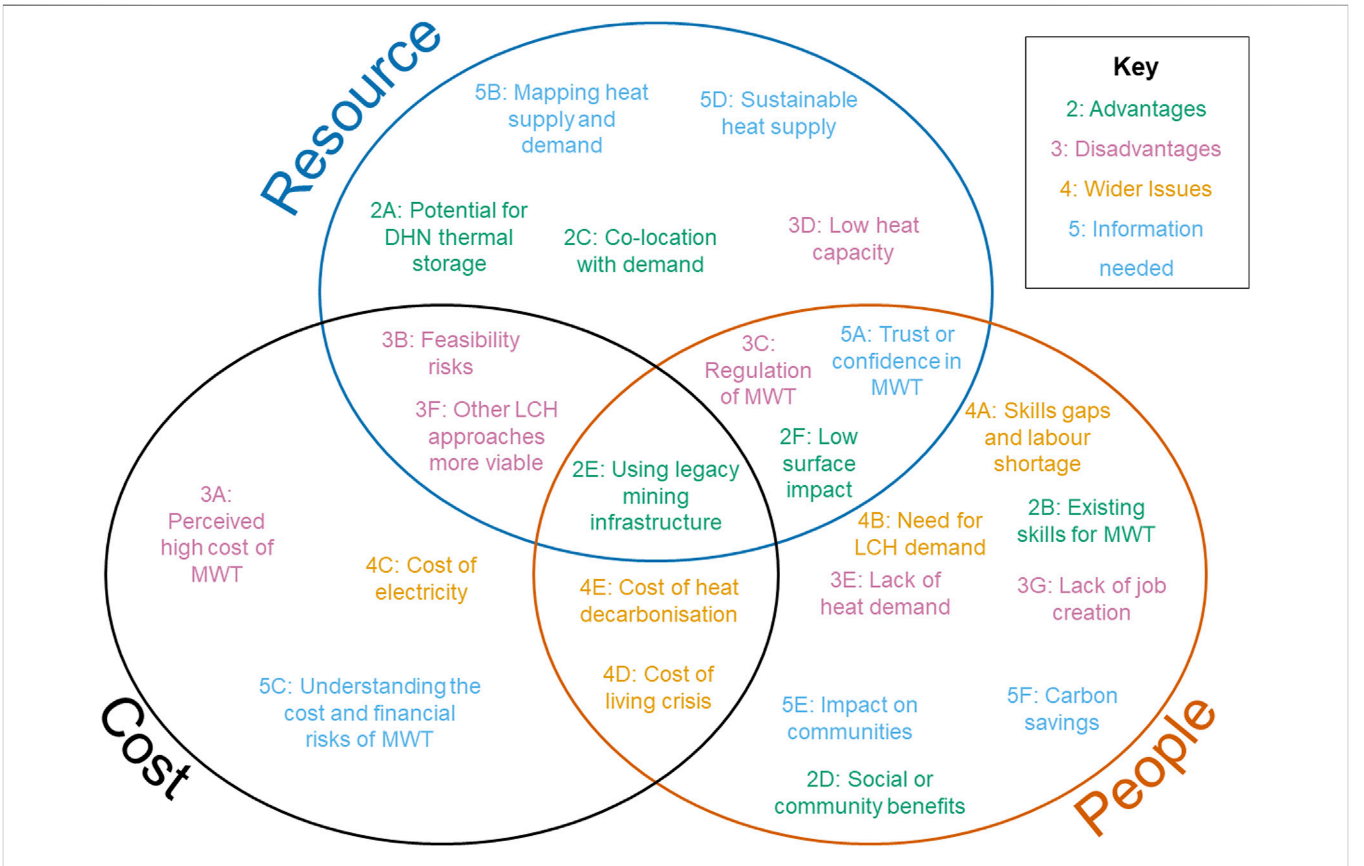

FIGURE 3 | Venn diagram showing how the factors mentioned in the interviews (perceived advantage and disadvantages, wider issues, and information needed) fit into three topics: resource, people and cost. The number labels refer to the table that each factor is mentioned in, and the letters refer its 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.

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, Gürsan 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., 2018a; Jagert et al., 2018; Shipton et al., 2024).

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 (Branford 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).

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.

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., 2018b; 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., 2022). 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.

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 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.

DATA AVAILABILITY STATEMENT

The data underpinning the findings of this study are openly available at: https://doi.org/10.15129/e7b2f725-2e9b-45cf-8c09-b063cdda1e65.

ETHICS STATEMENT

The studies involving humans were approved by the Department of Civil and Environmental Engineering Ethics Committee at the University of Strathclyde. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

KD: Conceptulisation, methodology, conducting the interviews, transcription, and formal analysis, writing the original manuscript, visualisation. ZS: Conceptualisation, funding acquisition and participant recruitment, supervision, reviewing and editing manuscript. JD: Supervision, reviewing and editing manuscript. JD: Supervision, reviewing and editing manuscript. All authors contributed to the article and approved the submitted version.

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CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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